

**SCHOOL OF
CIVIL ENGINEERING**

INDIANA

DEPARTMENT OF TRANSPORTATION

JOINT HIGHWAY RESEARCH PROJECT

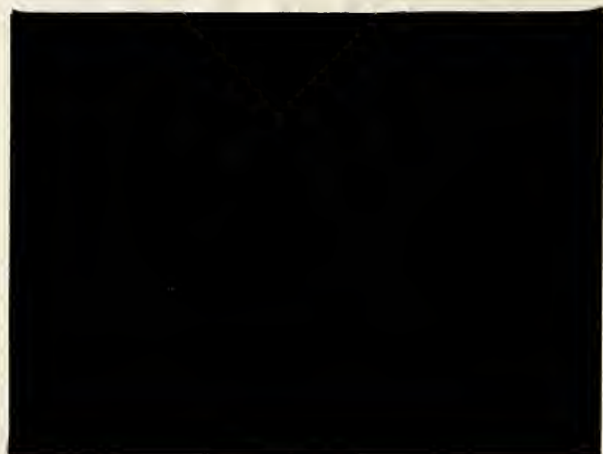
**FHWA/IN/JHRP-94/9
Final Report**

**BEHAVIOR OF CONCRETE BRIDGE
DECKS AND SLABS REINFORCED
WITH EPOXY-COATED STEEL**

Hendy O. Hasan and Julio A. Ramirez



PURDUE UNIVERSITY



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16. Abstract Thirty-four slab specimens with splices and transverse steel were tested in the laboratory to evaluate the structural performance of concrete bridge decks reinforced with epoxy-coated steel. Thirty specimens were tested under fatigue loading, and four were tested monotonically. Evaluations were made by comparing the performance of uncoated bar concrete specimens with that of epoxy-coated specimens under service and ultimate load conditions. In addition, a field evaluation of six bridges was conducted to assess the in-service condition of concrete bridge decks reinforced with epoxy-coated steel in Indiana. The laboratory results indicated fewer but wider cracks in specimens with epoxy-coated reinforcement. No significant differences in the first cracking load were found between uncoated specimens and epoxy-coated specimens. The splitting crack load and failure load were lower for specimens with epoxy-coated steel. Deflections of epoxy-coated specimens were larger. The differences in crack width and deflection were reduced with repeated loading. The average bond ratios were 0.78 and 0.75 for repeated loading tests. No signs of corrosion were found in the epoxy-coated steel samples extracted from cores taken in the six bridges evaluated. Evaluation of the field data revealed that the combination of adequate concrete cover and epoxy-coated steel has provided a good corrosion protection to date. This evaluation included the first bridge in Indiana where epoxy-coated reinforcement was placed (Circa 1976).			
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WITH EPOXY-COATED STEEL

by

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and

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Joint Highway Research Project

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and

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The contents of this report reflect the views of the author who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration and the Indiana Department of Transportation. This report does not constitute a standard, specification or regulation.

Purdue University
West Lafayette, IN 47907
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Behavior of Concrete Bridge Decks and Slabs Reinforced with Epoxy-Coated Steel

Implementation Report

The objective of this study was to evaluate the performance of epoxy-coated reinforcement in concrete bridge decks and slabs. This evaluation included an extensive laboratory program and a field survey of a representative sample of bridge decks and slabs in Indiana.

The Laboratory Phase consisted of testing 34 slab specimens under repeated loading. The performance evaluation was conducted by comparing the performance of specimens reinforced with epoxy-coated bars with that of companion identical specimens reinforced with uncoated bars. The comparative study included quantitative and qualitative aspects of bond strength, crack patterns, crack widths, and deflections.

The Field Phase dealt with the condition assessment of a representative sample of bridges in Indiana reinforced with epoxy-coated bars. The bridge sample was selected as representative in terms of degree of traffic, exposure to deicing salts and environmental conditions. The selected sample included the first bridge in Indiana with epoxy-coated reinforcement in the deck (7-40-6527). The sample included concrete decks supported on steel girders (flexible systems) and precast prestressed girders, and a reinforced concrete slab bridge. The site selection was fully coordinated with INDOT personnel. Evaluation of concrete core samples for compressive strength and unit weight, and of powder samples for chloride content was conducted by the Materials and Testing Division.

The field evaluation consisted of the following aspects:

- a. Identification of delaminated or spalled areas by visual inspection and using chain drag technique.
- b. Detailed mapping of crack patterns and crack widths.
- c. Determination of concrete cover using R-meter and extracted core samples with sections of reinforcement.
- d. Determination of concrete strength and unit weight by means of 6 inch diameter core samples.
- e. Determination of chloride concentration levels using concrete powder samples.
- f. Visual inspection of coating condition using samples extracted during the coring operation.

In summary, besides providing a better protection against the risk of corrosion, extra concrete cover also results in improved anchorage of the bars. Larger cover to diameter ratios are recommended in harsh environments to reduce the crack opening and should not be reduced with the expectation that the epoxy-coating will be the sole system of corrosion protection. Adequate inspection, finishing and curing represent solid construction practices and will lead to durable concrete. Use, proper manufacturing and handling of epoxy-coated bars are but a few of the aspects related to durable concrete bridge decks. The findings from this research study support the following recommendations:

1. The application of a single modification factor for splices of epoxy-coated bars of 1.35 is supported by the findings from this research study and others. INDOT is encouraged to incorporate this recommendation for the detailing of splices of

epoxy-coated bars in bridge decks.

2. Larger cover to bar diameter ratios (1.8 and higher) are recommended in harsh environments to reduce the crack opening and should not be reduced with the expectation that the epoxy-coating will be the sole system of corrosion protection. The current practice in Indiana of providing a total amount of concrete between the top mat of steel and the surface of the deck of at least 2.5 inches is adequate for bar sizes up to #11.
3. Although no corrosion and/or debonding was found in the epoxy-coated steel samples taken from the cores, further laboratory research and field monitoring on the durability of epoxy-coating are still needed. An extensive program to evaluate the condition of bridge decks in Indiana reinforced with epoxy-coated steel must be undertaken to establish their condition to date. This study would provide the reference point for future evaluations on the adequacy of epoxy-coated bars as a corrosion protection system for Indiana bridge decks.
4. Because of the potential for severe damage and disaster caused by an earthquake in the southern part of Indiana, research dealing with the performance of epoxy-coated bars under low cyclic loading is needed. Particularly as there is little knowledge on the behavior of concrete members reinforced with epoxy-coated steel under seismic loading and as this reinforcement is utilized extensively in bridge piers and foundations.

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CHAPTER 1 INTRODUCTION

1.1 Background

The safety and economic implications of the premature deterioration of reinforced concrete due to corrosion of reinforcing steel has been a major concern for structures exposed to corrosive environment. Several methods of corrosion protection have been used to prevent the corrosion of reinforcing steel such as increased concrete cover, epoxy-coating, cathodic protection, use of polymer concrete, sealing the concrete surface by a proper surface coating, and anodic inhibitors. The combination of protection, economic benefits and ease of use that the epoxy coating offers have made this method of corrosion protection widely accepted in nearly all types of structures throughout the United States.

The change in bond properties due to the presence of epoxy coating has been a major concern in using epoxy-coated steel in reinforced concrete structures. Another consideration has been the structural performance, i.e., deflection and cracking of members reinforced with this type of steel. Research in the past 20 years has shown that epoxy-coating results in a wide range of bond strength reduction [1-8]. The greatest bond reduction occurred in splitting type failure mode [3]. It was also reported that members with epoxy-coated steel have fewer but wider cracks compared to members with uncoated steel. Deflections for both type members were found not to differ significantly. Results of these studies have led to change in ACI and AASHTO design specifications for development length of reinforcement.

Concrete bridge structures are typically subjected to high cycle fatigue loading during their structural life. In a bridge deck structure, the stress range is provided by the live load superimposed on the dead load. The live load is a cyclic repeated load provided by traffic. On the other hand, the current ACI 318-89 Building Code [9] specification for development length for epoxy-coated bars was based on research data from static loading tests by Treece and Jirsa [3]. The tests consisted of 21 specimens, of which 12 contained epoxy-coated reinforcement and were tested monotonically. Therefore, to better representing the real loading situation, research in the area of members with epoxy-coated bars subjected to fatigue loading is necessary.

Recent conflicting findings have been reported in various other research studies and from observed field experiences related to the corrosion of epoxy coated reinforcement. Thus, it was felt that a field condition assessment of a representative sample of bridges in Indiana was necessary. This evaluation would provide hard data on the performance of epoxy-coated reinforcement under the environmental conditions and construction and inspection practices found in the state.

1.2 Scope and Objective

The main objective of this study was to evaluate the performance of epoxy-coated reinforcement in concrete bridge decks and slabs. This evaluation was conducted by means of a laboratory experimental program together with a field survey of a representative sample of bridge decks in the state of Indiana.

The laboratory phase included testing of 34 slab specimens under repeated loading.

The performance evaluation include the quantitative and qualitative aspects of bond strength, crack patterns, crack widths, and deflections.

The field phase dealt with the condition assessment of 6 bridges in Indiana reinforced with epoxy-coated reinforcement. This sample was selected as a representative sample of bridges in Indiana in terms of traffic, deicing salt exposure and environmental conditions. The first bridge in Indiana where epoxy-coated reinforcement was placed in the concrete deck is part of the sample evaluated.

1.3 Summary

Indiana is in need of an evaluation of the performance to date of concrete bridge decks and slabs reinforced with epoxy-coated steel for improved economy and performance of bridges in the state. The research described in this report addresses the structural performance of concrete slabs reinforced with epoxy-coated bars under repeated loading. Also, a condition assessment task provided information on the performance of bridge decks in Indiana reinforced with epoxy-coated steel.

In Chapter 2, a literature review of relevant works is presented. A detailed description of the laboratory phase is given in Chapter 3. The results from the experimental program are presented in Chapter 4. The field evaluation phase and significant findings are covered in Chapter 5. Finally, Chapter 6 contains a summary of the findings from this study, the general conclusions and final recommendations.

CHAPTER 2 BACKGROUND ON STRUCTURAL PERFORMANCE OF MEMBERS REINFORCED WITH EPOXY-COATED STEEL

2.1 Introduction

The use of epoxy-coated steel as a corrosion prevention technique has been a common practice in bridge and highway reinforced concrete structures. As a method of corrosion prevention, epoxy-coated steel offers the advantages of economy, effectiveness, and ease of use. However, there are concerns with the bond properties of coated steel and its effects on the performance of structures. Evidence of reduced bond strength as well as inferior structural performance has been reported in literature.[1-8] A brief review of the previous studies conducted on concrete members reinforced with epoxy-coated steel will be given first, followed by the discussion on the current ACI 318-89 building code [9] and 1989 AASHTO design provisions [10] for development length and fatigue.

2.2 Previous Studies on Epoxy-Coated Bars

2.2.1. Clifton and Mathey (1976)

Clifton and Mathey [1] reported test results of 34 pullout specimens. The study included 23 specimens with epoxy-coated bars, 5 specimens with uncoated reinforcing bars, and 6 specimens with polyvinyl chloride-coated bars. The pullout specimens were 10-in. x 10-in. x 12-in. concrete prism with 4 ft embedment length. Reinforcement was

provided by #6 bars with either barrel (B) or diamond (D) deformation patterns. Coating thickness ranged from 1 - 11 mils with the exception of 2 bars having a coating thickness of 25 mils. All of the uncoated bars as well as the coated bars with 1-to-11 mils yielded in the tests. Critical bond strength is defined as the lesser of the bond stress corresponding to a loaded-end slip of 0.01 in. or that corresponding to free-end slip of 0.002 in. It was reported that bars with epoxy coating approximate 10 mils or less in thickness developed essentially the same bond strength as the uncoated bars. For polyvinyl coating or epoxy coating with 25 mils in thickness, the bond strength was considerably less for coated bars than for uncoated bars. Based on the comparison of critical bond strength, it was recommended that epoxy-coated steels with a coating thickness less than 10 mils are acceptable for use in concrete flexural members.

2.2.2 Johnston and Zia (1982)

Johnston and Zia [2] of the University of North Carolina conducted static tests on 6 companion slab specimens for comparison of cracking behavior. Results from the slab specimens showed little difference in terms of deflection, crack widths and spacing, and ultimate strength between coated and uncoated bar specimens. Four specimens failed in flexure and two failed in shear. The failure load for epoxy-coated bar specimens averaged 4% lower than uncoated bar specimens.

Comparisons of the bar load versus bar slip were evaluated using the results of static tests on 26 companion beam-end specimens as well as fatigue tests on 14 companion beam end specimens. Based on the same critical slip criteria as used in Clifton

and Mathey [1] study, results of beam end static tests showed an average of 32% lower bond strength with epoxy-coated bars compared with uncoated bars. For development lengths greater than 12 in., the bond strengths were found to be 15% lower for epoxy-coated bars. A 1.15 basic development length modification factor was proposed to account for the reduction in bond strength when using epoxy-coated bars. The bond fatigue tests showed results similar to those found with static tests.

2.2.3 Treece and Jirsa (1987)

An experimental study to determine the bond strength of epoxy-coated and uncoated bars in tension was carried out by Treece and Jirsa at the University of Texas-Austin [3]. The test program included static tests of 21 beam specimens reinforced with either #6 or #11 bars spliced in the center of the beam. Coating thickness was either 5 mils or 12 mils and three nominal concrete strengths of 4 ksi, 8 ksi, and 12 ksi were used in the study. Seventeen of the specimens were top cast and four were bottom cast. The test set-up was designed to produce a constant moment region in the midspan region. All the specimens failed in a splitting failure mode.

Evaluation included measured bond strength, crack width and spacing, and stiffness of the beams. Results showed that epoxy-coated bars developed 66% of the bond of uncoated bars. Little difference was found in terms of stiffness between coated and uncoated bar specimens. Fewer and wider cracks were found in epoxy-coated specimens.

2.2.4 Cleary and Ramirez (1989, 1991, 1992)

Cleary and Ramirez [4,20,11] carried out an experimental investigation to evaluate the flexural bond characteristic of epoxy coated reinforcing bars in concrete bridge deck slabs under static loading. Specimens were similar to those used in the Treece and Jirsa [3] study. Test variables were splice length and concrete compressive strength. Test results indicated that epoxy coating causes a significant reduction in bond strength. Based on a very small amount of sample, it was found that the reduction in bond strength increased with increasing anchorage length and increasing concrete strength.

Bond of epoxy-coated reinforcement under repeated loading was investigated in another experimental study by Cleary and Ramirez [11]. The experimental program involved nine sets of companion specimens tested under repeated loading. In addition, five specimens containing epoxy-coated steel were tested monotonically. The specimens and test set-up were similar to the previous work [4]. Test variables included splice length, concrete strength, stress range, and number of loading cycles.

Test results indicated that the failure bond stress ratio ranged from 0.82 to 0.96 with an average of 0.88. In terms of deflection and crack width, it was found that specimens with epoxy coating bars had fewer but wider cracks, and larger deflections compared to uncoated bars specimens. The differences in crack widths and deflections were reduced with increasing number of cycles of repeated loading. Deflections increased with repeated loading for both types of reinforcement, especially in the first 200,000 cycles, and the changes were larger in uncoated bar specimens. It was reported that concrete strength and stress range had no influence on the compared deflections.

Furthermore, the stress range did not affect the near failure deflections with either type of reinforcement, or the splitting load in epoxy-coated bar specimens.

2.2.5 Choi, Hadje-Ghaffari, Darwin, and McCabe (1990)

Choi et al. [5] reported in 1990 the test results of 284 beam-end specimens and 15 splice specimens. Parameters evaluated included the effect of coating thickness, deformation pattern, and bar size on the reduction in bond strength caused by epoxy coating. Bar sizes used were No.5, No.6, No.8, and No.11 bars. The average coating thickness ranging from 3 mils to 17 mils. Three deformation patterns: S, C, N, were evaluated. Deformation pattern S consisted of ribs perpendicular to the axis of the bar. Deformation pattern C consisted of diagonal ribs inclined at an angle of 60° with respect to the axis of the bar. Deformation pattern N consisted of diagonal ribs inclined at an angle of 70° with respect to the axis of the bar. All the specimens failed in splitting failure mode.

The test results showed a significant reduction in bond strength for epoxy coatings in the range of 5 to 12 mils although the extent of reduction was less than used to select development length modification factors in the ACI 318-89 Building Code [9] and 1989 AASHTO Bridge Specifications [10]. It was observed that coating thickness has little effect on the bond reduction for No.6 bars and larger. For No.5 bars and smaller, thicker coating caused greater bond reduction. Increasing the bar size generally increased the bond reduction caused by epoxy coating. In terms of deformation pattern, it was concluded that bars with relatively larger bearing areas are affected less by the coating

than bars with smaller bearing areas.

2.2.6 Hester, Salamizavaregh, Darwin and McCabe (1991)

Hester et al. [6] from University of Kansas conducted an experimental investigation on the effects of epoxy coating and transverse reinforcement on the bond strength of splices. The test program included static tests of 65 beam and slab splice specimens containing No.6 and No.8 bars. The average coating thickness ranged from 6 to 11 mils. The bar deformation pattern were S, C and N. The beam specimens were similar to those tested by Treece and Jirsa, and Choi et al.. The slab specimens were similar to those tested by Cleary and Ramirez. All specimens failed in splitting mode.

Tests results indicated a significant bond strength reduction caused by epoxy coatings. It was found that the reduction in splice strength is independent of the degree of transverse reinforcement. It was also noticed that the transverse reinforcement increased the splice strength for all bar surface conditions. The authors recommended the use of a single development length modification factor of 1.35 in the ACI Building Code. The same factor can also be applied to the AASHTO Bridge Specification for bars with transverse reinforcement providing $K_{tr} < 3.0$. In the case of $K_{tr} > 3.0$, this factor should change to 1.20.

2.2.7 Hamad and Jirsa (1993)

In 1993, Hamad and Jirsa [12] reported results of an experimental investigation of the effect of epoxy-coated transverse reinforcement on the strength of epoxy-coated bar splices. Twelve beam specimens were tested with negative bending with multiple splices

in a constant moment region at the center of the beam. The test variables were the amount of transverse reinforcement, bar sizes (No. 6 and No. 11 bars), and bar spacing. The nominal coating thickness was 8 mils. All beams were tested monotonically until failure by splitting of the concrete cover in the splice region. K_{tr} was larger than 1 for all the beams. It was found that transverse reinforcement improved the deformation capacity of the beams and the bond strength of splices. The improvement in bond strength was greater for epoxy-coated bar splices than uncoated bar splices and was independent of the number of splices, bar size or bar spacing. The bond ratio for No.11 bar splices increased from 0.74 without stirrups to 0.81 when three No. 3 ties were provided in the 30 in. splice region, and to 0.84 when six No. 3 ties were provided. For No. 6 bars, the bond ratio increased from 0.67 without stirrups to 0.74 when three No. 3 ties were provided in the 18 in. splice region. The authors also proposed modification of the ACI 318-89 development and splice length provisions.

2.3 ACI 318-89 and AASHTO Design Provisions

2.3.1 Development Length

The ACI 318-89 Building Code [9] specifies that the development length for tensile reinforcement be computed as the product of the basic development length l_{db} , and the applicable modification factor. The basic development length, l_{db} , is computed as :

$$\begin{aligned}
l_{db} &= 0.04 A_b f_y / \sqrt{f'_c} && \text{for \#11 bars and smaller and deformed wire} \\
&0.085 f_y / \sqrt{f'_c} && \text{for \#14 bars} \\
&0.125 f_y / \sqrt{f'_c} && \text{for \#18 bars}
\end{aligned} \tag{2.1}$$

To account for bar spacing, amount of cover and enclosing transverse reinforcement, the modification factor is 2.0 if cover is less than d_b or clear spacing is less than $2 d_b$. No modification factor is required when certain minimum cover or transverse steel requirements are met. For all other conditions, the factor is 1.4. The modification factor may be multiplied by a factor of 0.80 for widely spaced bars, 0.75 for closely spaced ties, 1.3 for top cast bars or lightweight concrete. To prevent bar yielding, the development length should be greater than $0.03 d_b f_y / \sqrt{f'_c}$. To account for the reduced bond strength in epoxy-coated bars, section 12.2.4.3 ACI code specifies a modification factor of 1.5 when cover is less than $3 d_b$ or clear spacing between bars is $< 6 d_b$, and 1.2 for all other conditions. As a comparison, these factors are 1.5 and 1.15 in the AASHTO [10] Specifications. Notice the ACI code required that the product of factors account for top cast and epoxy-coating should not be taken greater than 1.7.

The ACI 318-89 [9] does not required specific checks for bond stress, however, the formula for l_{db} required is based on bond stress, defined as a shear force per unit area of bar surface being developed between two sections along the bars.

2.3.2 High Cycle Fatigue

Cyclic loading generally can be divided into two categories: low cycle loading and high cycle loading. The low cycle loading is a load history with few cycles of loading but

very large bond stress range (> 600 psi) as commonly encountered in seismic and high wind loading. The high cycle loading is a load history containing many cycles, typically thousands or millions, but at low bond stress range (< 300 psi) as often happens in bridge and offshore structures or structures supporting vibrating machinery. High cycle fatigue is considered a problem at service load level, while low cycle fatigue produces problems at the ultimate limit state.

ACI committee 215 [13] recommended that the stress range f_{cr} in concrete be calculated as:

$$f_{cr} = 0.4 f'_c + 0.47 f_{min} \quad (2.2)$$

f_{cr} should not exceed $0.50 f'_c$ when the minimum stress is zero. For straight deformed bars the stress range should not exceed 21 ksi.

AASHTO [10] recommended that the stress range due to live loads and impact in reinforcing bars should not exceed :

$$f_r = 21 - 0.33 f_{min} + 8 \frac{r}{h} \quad (2.3)$$

f_r = stress range, ksi

f_{min} = minimum stress level, ksi

r/h = ratio of the base radius to height of rolled transverse deformation

= 0.3 if r/h is unknown

2.4 Summary

A brief review of the studies of epoxy-coated bars has been presented. It was reported that epoxy coating reduced the bond strength of concrete members reinforced with epoxy-coated bars from 10% to 37% . It was found that members with epoxy-coated bars have fewer but wider cracks. The effect of transverse steel is to increase the bond strength.

Previous study on the bond behavior under fatigue loading revealed that repeated loading reduced the bond at failure. Repeated loading increased the deflection for both types of steel with the larger change in uncoated steel. It was found that the difference in crack widths and deflections between coated and uncoated steel were reduced with the increasing number of cycles.

A summary of ACI [9] and AASHTO [10] design approach for repeated loading has also been presented. The design equations specify a stress range limit rather than a bond stress limit because they are based on the assumption that steel or concrete will fail in fatigue before the bond strength is exhausted.

In the next chapter, a detailed research plan to evaluate the structural performance of bridge decks subjected to repeated loading will be presented. The chapter includes a description of the test specimens, fabrication, the test procedure and variables.

CHAPTER 3 LABORATORY PHASE : STRUCTURAL EVALUATION

3.1 Introduction

The overall research study consists of two phases; a Laboratory Phase and a Field Phase. In this chapter, the details of the Laboratory Phase are given. The Field Phase is presented in Chapter 5. The purpose of the Laboratory Phase is to compare the structural behavior of reinforced concrete bridge decks reinforced with epoxy-coated bar with those reinforced with uncoated bars. Comparison of the performance is made at both service load level and ultimate strength. Evaluation of the service load performance includes the consideration of cracking, deflections and fatigue.

3.2 Experimental Program

The laboratory program consisted of a series of 34 reinforced concrete slab specimens that model a bridge deck section. Two types of test specimens were used in the laboratory phase, Type A and Type B. The Type A specimen was 13 feet long with a cross section of 24 inches wide and 8 inches deep. Reinforcement consisted of 3 #7 bars spaced at 6.5 inches with a 12 inch splice at midspan. The Type B specimen was also 13 feet long, but with a cross section of 28 inches wide and 12 inches deep, reinforced with 3 #11 bars spaced at 8 inches, and a 28 inch splice at midspan. Both types of specimen have 2.5 inches clear concrete cover and transverse steel of #3 bars spaced at 6 inches. The splice was designed to fail prior to yielding of the steel. Each slab specimen was tested as a simply supported beam with a 4 foot midspan length. Two equal concentrated

loads were applied at 6 inches from the ends, giving a constant negative bending moment between the supports to facilitate observation and measurement of cracks. Loads were applied with an Amsler hydraulic pulsator. Of the 34 slab specimens tested, 30 slabs were tested under repeated loading, and the remaining four were tested with a single load cycle to failure. The test program is shown in Table 3.1.

The laboratory test program was carried out in three phases: Each phase is identified as Phase-I, Phase-II, and Phase-III respectively. Table 3.2 shows the specimen with its corresponding phase number, cast number and cast date.

The following section describes in detail the test specimens, instrumentation, and test procedure. The criteria used in selecting each test variable, and the reasons for each measurement are discussed.

3.2.1 Test Specimens

The test specimens were designed to model a bridge deck in the direction perpendicular to the main longitudinal load-carrying members. Figure 3.1 shows the evolution of the test specimen. The width of the specimens represents the width of a section through the deck, with the supports simulating the beams under the deck. The #7 and #11 bar sizes used for longitudinal reinforcement represent the lower and upper bounds of typical main longitudinal bar sizes used in Indiana for reinforced concrete bridge decks and slabs. Transverse steel, consisting of #3 epoxy-coated bar spaced at 6 inches on centers, models the typical amount of #4 bar at 12 inches. The transverse steel was fully anchored through standard hooks at ends. Grade 60 steel was used consistently.

The concrete cover of 2.5 inches represents a minimum for a typical negative moment region in a continuous bridge deck or slab. This region, at the top of the slab near and over the continuous support, will typically be the one subjected to the most severe exposure conditions. The splice length was chosen using the Orangun equation [14]

$$u = \left(1.2 + \frac{3c}{d_b} + \frac{50d_b}{l_s} + K_{tr}\right) \sqrt{f'_c} \text{ which indicates that a 12 inch and a 28 inch splice}$$

would not be expected to yield with 3000 psi concrete. Two equal concentrated loads were applied at 6 inches from the end of the beam with an Amsler hydraulic pulsator. For the repeated loading tests, the pulsator was operated at a rate of 260 cycles per minute. The specimen was supported 4 feet from the loading points giving a 4 foot long midspan subjected to a negative uniform moment. The uniform moment region allowed uncontrolled formation of flexural cracks and provided for convenient observation and measurement of developing cracks. Figure 3.2 shows the detail of the test specimen and loading arrangement.

3.2.2 Concrete

Concrete was batched at a local Ready-Mix plant and placed in the lab. Each cast produced two companion Type A specimens and two companion Type B specimens. A specimen containing uncoated steel and a companion specimen with epoxy-coated steel were cast together to ensure similar concrete properties for each companion set. The concrete properties are given in Table 3.3, and the strength curves for each cast are presented in Figure 3.3.

3.2.3 Reinforcement

All reinforcement was Grade 60 steel. The physical and mechanical properties of the reinforcement are given in Table 3.4. Bar samples from epoxy-coated reinforcement were inspected by the Materials and Testing Division of INDOT. These samples meet the minimum standard of yield strength and coating thickness. Although the bars were from different heats, the properties were similar to each other and met the ASTM standards [15]. The reinforcement is shown in Figure 3.4.

The standard INDOT coating thickness limits were met in 30 specimens. An extra thick coating was used in 4 specimens to determine the effect of extra thickness of coating. To evaluate the influence of steel deformation pattern, two specimens were reinforced with bars with a diamond deformation pattern. The thickness of epoxy coating was measured along the longitudinal rib of each bar with a Nordsen dry film gage. The distribution of coating thickness is shown in Figure 3.5. The average coating thickness was approximately 9 mils for normal coating of No. 3, No. 7, and No. 11 bars. The extra thick coating for No. 7 bars with a spiral deformation pattern was 22.7 mils, 15.5 mils for No. 11 bars with a spiral pattern, and 26.1 mils for No. 11 diamond pattern bars.

3.2.4 Fabrication

Each cast produced a set of Type A and a set of Type B specimens. Both types came with a specimen containing uncoated steel and a companion specimen containing epoxy-coated steel. The casting was done indoors, with the concrete being placed directly

from the Ready-Mix truck. For Type A specimens, the concrete was placed in a single lift and mechanically vibrated. For Type B specimens, the concrete was poured in 2 lifts and also mechanically vibrated. Slump measurements were taken and flexure beams and cylinders were made at this time. After placement and finishing of the concrete, the beams were covered with plastic sheeting to reduce shrinkage cracking. The plastic cover was removed and the cylinders and flexure beams were demolded after 72 hours. The formwork was stripped after 7 days.

3.2.5 Instrumentation

Figure 3.6 shows the instrumentation used in testing of the specimen. Deflections at the beam ends and centerline were measured using Linear Variable Differential Transformers (LVDTs). Deflection data were used to compare the stiffness and the rate of stiffness degradation of the companion specimens.

Electrical resistance foil strain gages with a 1/8 inch gage length were placed on each reinforcing bar 5 inches beyond the end of the splice. These measured the strain in the reinforcement.

For specimen series 7241, two-inch gage length electrical resistance foil strain gages were placed on each side of the beam at midspan. The gages were located in the compression zone 1/2 inch and 1-1/4 inches from the bottom of the beam. For all other specimens, three two-inch gage length electrical resistance foil strain gages were placed in the compression zone at both sides of the specimen. These three two-inch gages, located at midspan, and 5 inches from both ends of splice, were used to determine the

strain profile in the region.

For Type A specimens, loads were measured using a 10 kip load cell at one end of the beam and a 20 kip load cell at the other end. For Type B specimens, the load cells used were 50 kip and 100 kip. The load cells were removed during application of the repeated load cycles, and the load magnitude was monitored by the testing machine. Due to the limited capacity of the Amsler loading ram, for the failure cycle of Type B specimens, loading was applied instead by a pair of Parker Hannifin Hydraulic Cylinders.

Figure 3.7 shows the system used to measure the slip of the reinforcement. In this system, 0.058 inch diameter guitar strings were attached to the outer reinforcing bars at each end of the splice. Tygon tubing with an inside diameter of 0.0625 inch was filled with graphite grease to ensure the free movement of the wire. The wires were passed through the tubing and out of the concrete. The external end of each wire was attached to an LVDT mounted on the concrete surface. Tension was maintained on the wires with a spring on the mounting apparatus. As the reinforcement moved it pulled or pushed the wire producing a corresponding movement of the LVDT core. A photograph of a mounted slip gage is shown in Figure 3.8.

The slip wire exits the beam approximately 3 to 9 inches from the end of the splice. A flexural crack crossing the wire in this length is presumed to cause an apparent slip equal to the crack width. A Whitmore gage with a resolution of 0.0001 inches was used to measure the width of any cracks that cross the slip wire. The crack width was assumed to vary linearly from the end of the crack to the concrete surface. Using this assumption, the width of the crack at the depth of the wire was determined and subtracted

from the measured slip.

The width of all other flexural cracks in the uniform moment region was measured with an Edmund Direct Measuring Microscope 50X with a 0.001 inch accuracy. The width was measured at three locations. The surface of the beam was whitewashed to aid in crack detection. A specimen, prepared for testing, is shown in Figure 3.9.

3.2.6 Test Parameters and Variables

In the test program, the specimen dimensions, including the beam length, width, depth, bar size, concrete cover, and splice lengths were held constant. The concrete strength, peak stress and stress range for repeating loading, bar deformation pattern and coating thickness varied. The combination of variables used for the 34 tests is shown in Table 3.1. The first letter of the specimen code indicates epoxy-coated or uncoated steel. The next two digits are the bar size. The following 2 digits are the peak stress used in repeated loading. The last digit is the specimen number tested with the same variable combination. For the extra coating thickness specimens, the D indicates the diamond deformation pattern, S indicates the spiral deformation pattern, and X indicates the extra thickness of coating. The variable combinations were selected to cover a range of load cases.

The splice lengths were 12 inches and 28 inches. The reasons for these selections are given in section 3.2.1 The concrete strengths used are discussed in section 3.2.2.

The stress ranges used in the reinforcement were 8.74 ksi and 15 ksi at flexural crack locations. The stress was calculated assuming a cracked transformed section and a

Hognestadt stress distribution in the concrete compression zone. The stress range was selected to prevent failure of the reinforcement in fatigue. The threshold value of stress range for fatigue failure of reinforcement is 20 ksi [13]. For high cycle fatigue of uncoated bars, a stress range in excess of 40% of the steel yield strength of the reinforcement in anchorage may reduce bond strength at failure [16]. Since the stress ranges used in tests of this study fall below this limit, the epoxy coating may be considered the dominant factor in the change of bond strength.

The maximum and minimum stress values used in the repeated loading were selected to fall in the upper limits of what are considered service loads. In allowable stress design, a stress of $0.6 f_y$ or 36 ksi is used as the upper stress. For Type A specimens, the peak stresses of 24 ksi, 30 ksi, and 36 ksi were used. For Type B specimens, the peak stresses used were 24 ksi and 30 ksi. 1,000,000 cycles were used in the repeated loading test, which represents a peak load occurring every 10.5 minutes of a 20 year bridge deck life.

3.2.7 Test Procedure

The following procedure was followed in testing the beams. Each test specimen was initially cracked by the application of 2 or 3 quasi-static load cycles, up to the load corresponding to the peak stress used in the repeated load test. All of the previously described measurements were made during this monotonic loading. In addition, the stiffness was measured for use in the adjustment of loads for dynamic effects of repeated loading.

After the initial cracking of the beam the load cells were removed and the beam was repeatedly loaded between the maximum and the minimum stress values with the Amsler Hydraulic Pulsator. The loading rate used was 260 cycles per minute, limited by the testing machines and the specimen stiffness. The loading rate is close to the bounce mode of excitation for trucks [17]. The repeated loads were applied in blocks of approximately 100,000 cycles for the first 300,000 cycles. For the remaining loading cycles, the number of cycles per block was increased to 150,000 cycles with either the second to last or the last loading block at 100,000 cycles per block.

Between each block of repeated loads, another monotonic load cycle was applied in order to record the transducer measurements and crack widths. The procedure was repeated until the full number of cycles had been applied. The beam was then loaded monotonically until a bond failure occurred.

Two sets of epoxy-coated and uncoated companion specimen were tested to failure with a single monotonic load cycle. The results of these tests were used to evaluate changes in the behavior of the beams with epoxy-coated reinforcement due to repeated loading.

3.3 Summary

The details of the laboratory program were described in this chapter. The main objective of this program is to evaluate the structural behavior of typical concrete bridge decks and slabs reinforced with epoxy-coated steel. The evaluation is conducted by comparing the performance of specimens reinforced with epoxy coated steel with the

performance of companion, otherwise identical specimens reinforced with uncoated steel.

In Chapter 4, the findings from the laboratory program are presented.

Table 3.1. Test Program

Specimen (Type A)	Bar Size	Deform. Pattern	Avg.Coat Thickn. (mils)	Cover (in)	ls (in)	f'c (ksi)	Peak Stress (ksi)	Stress Range (ksi)	# of Cycles
U7241	#7	Spiral	9.05	2.5	12	3	24	8.74	1,000,000
E7241	#7	Spiral	9.05	2.5	12	3	24	8.74	1,000,000
U7242	#7	Spiral	9.05	2.5	12	4.7	24	8.74	1,000,000
E7242	#7	Spiral	9.05	2.5	12	4.7	24	8.74	1,000,000
U7361	#7	Spiral	9.05	2.5	12	5.2	36	8.74	1,000,000
E7361	#7	Spiral	9.05	2.5	12	5.2	36	8.74	1,000,000
U7362	#7	Spiral	9.05	2.5	12	5.3	36	8.74	1,000,000
E7362	#7	Spiral	9.05	2.5	12	5.3	36	8.74	600,000
U7363	#7	Spiral	9.05	2.5	12	4	36	15	1,000,000
E7363	#7	Spiral	9.05	2.5	12	4	36	15	1,000,000
U7301	#7	Spiral	9.05	2.5	12	3	30	8.74	1,000,000
E7301	#7	Spiral	9.05	2.5	12	3	30	8.74	1,000,000
U736SX	#7	Spiral	22.65	2.5	12	5.2	36	8.74	1,000,000
E736SX	#7	Spiral	22.65	2.5	12	5.2	36	8.74	710,000
U7STAT	#7	Spiral	9.05	2.5	12	3.9	static	-	1
E7STAT	#7	Spiral	9.05	2.5	12	3.9	static	-	1

Table 3.1. (Continued)

Specimen (Type B)	Bar Size	Deform. Pattern	Avg. Coat Thickn. (mils)	Cover (in)	ls (in)	f'c (ksi)	Peak Stress (ksi)	Stress Range (ksi)	# of Cycles
U11241	#11	Spiral	9.2	2.5	28	3	24	8.74	1,000,000
E11241	#11	Spiral	9.2	2.5	28	3	24	8.74	1,000,000
U11242	#11	Spiral	9.2	2.5	28	4.7	24	8.74	1,000,000
E11242	#11	Spiral	9.2	2.5	28	4.7	24	8.74	1,000,000
U11243	#11	Spiral	9.2	2.5	28	3	24	15	1,000,000
E11243	#11	Spiral	9.2	2.5	28	3	24	15	1,000,000
U11301	#11	Spiral	9.2	2.5	28	5.2	30	8.74	1,000,000
E11301	#11	Spiral	9.2	2.5	28	5.2	30	8.74	1,000,000
U11302	#11	Spiral	9.2	2.5	28	5.3	30	8.74	1,000,000
E11302	#11	Spiral	9.2	2.5	28	5.3	30	8.74	1,000,000
U11303	#11	Spiral	9.2	2.5	28	4	30	15	1,000,000
E11303	#11	Spiral	9.2	2.5	28	4	30	15	336,000
U11STAT	#11	Spiral	9.2	2.5	28	3.8	static	-	1
E11STAT	#11	Spiral	9.2	2.5	28	3.8	static	-	1
U1130SX	#11	Spiral	15.5	2.5	28	5.2	30	8.74	1,000,000
E1130SX	#11	Spiral	15.5	2.5	28	5.2	30	8.74	1,000,000
U1130DX	#11	Diamond	26.1	2.5	28	4.3	30	8.74	1,000,000
E1130DX	#11	Diamond	26.1	2.5	28	4.3	30	8.74	1,700

Table 3.2. Test Phases, Cast Number, and Specimen

Type A specimens				Type B specimens			
Test Phase	Cast Number	Cast Date	Specimen	Test Phase	Cast Number	Cast Date	Specimen
I	1	1/28/91	U7241	I	1	1/28/91	U11241
I	1	1/28/91	E7241	I	1	1/28/91	E11241
I	2	3/15/91	U7242	I	2	3/15/91	U11242
I	2	3/15/91	E7242	I	2	3/15/91	E11242
I	3	6/3/91	U7361	II	5	11/1/91	U11243
I	3	6/3/91	E7361	II	5	11/1/91	E11243
I	4	7/31/91	U7362	I	3	6/3/91	U11301
I	4	7/31/91	E7362	I	3	6/3/91	E11301
II	6	2/12/92	U7363	I	4	7/31/91	U11302
II	6	2/12/92	E7363	I	4	7/31/91	E11302
II	5	11/1/91	U7301	II	46	2/12/92	U11303
II	5	11/1/91	E7301	II	6	2/12/92	E11303
III	8	8/14/92	U736SX	II	7	6/8/92	U11STAT
III	8	8/14/92	E736SX	II	7	6/8/92	E11STAT
II	7	6/8/92	U7STAT	III	8	8/14/92	U1130SX
II	7	6/8/92	E7STAT	III	8	8/14/92	E1130SX
				III	9	10/9/92	U1130DX
				III	9	10/9/92	E1130DX

Table 3.3 Concrete Properties

Specimen	Type A Specimens				Type B Specimens				
	Slump (inches)	28 Day Strength (psi)	Test		Specimen	Slump (inches)	28 Day Strength (psi)	Age (days)	Test
			Age (days)	Comp (psi)					
U7241	-	3018	48	3160	U11241	-	3018	93	3172
E7241	-	3018	57	3043	E11241	-	3018	105	2918
U7242	-	4651	124	4769	U11242	-	4651	71	4739
E7242	-	4651	132	4663	E11242	-	4651	94	4669
U7361	-	5111	70	5346	U11301	-	5111	96	5287
E7361	-	5111	85	5264	E11301	-	5111	108	5258
U7362	-	5099	129	5134	U11302	-	5099	61	5305
E7362	-	5099	100	5193	E11302	-	5099	76	5453
U7301	7	3230	60	3083	U11243	7	3230	116	2965
E7301	7	3230	80	3089	E11243	7	3230	130	2924
U7363	6.5	4056	52	4050	U11303	6.5	4056	31	4097
E7363	6.5	4056	68	3855	E11303	6.5	4056	41	3926
U7STAT	4.5	3832	28	3832	U11STAT	4.5	3832	44	-
E7STAT	4.5	3832	30	3920	E11STAT	4.5	3832	46	-
U736SX	4	4860	52	5352	U1130SX	4	4860	110	5252
E736SX	4	4860	70	5299	E1130SX	4	4860	151	5028
					U1130DX	6	4482	98	3873
					E1130DX	6	4482	102	4126
									8349

Table 3.4 Physical and Mechanical Properties of Reinforcement

	Phase I						Phase II						Phase III						ASTM	
	# 7 Bars			#11 Bars			# 7 Bars			#11 Bars			# 7 Bars			#11 Bars			# 7 Bar	#11 Bar
	Unc	Epo		Unc	Epo		Unc	Epo		Unc	Epo		Unc	Epo		Unc	Epo			
Average Gap (in)	0.273	0.253		0.291	0.283		0.273	0.253		0.291	0.283		0.188	0.204		0.18	0.18		0.334	0.54
Average Spacing (in)	0.545	0.545		0.857	0.636		0.545	0.545		0.857	0.636		0.522	0.522		0.8	0.8		0.612	0.987
Average Height (in)	0.045	0.047		0.077	0.071		0.045	0.047		0.077	0.071		0.048	0.048		0.07	0.07		0.044	0.071
Var. Weight (%)	-3.9	-4.1		-4.1	-4.4		-3.9	-3.4		-5	-5.6		-3.6	-3.6		-5	-5		6	6
Yield Strength (psi)	65.8	68.3		68.3	69.2		69.2	63.3		67.9	74.4		65.8	65.8		67.6	67.6		60000	60000
Tensile Str. (psi)	110	102.5		102	108.3		111.7	103.3		102.2	110.6		106.7	106.7		102	102		90000	90000
Elong. in 8" (%)	14	13		13	14		15	14		15	8		12	12		13	13		8	7
Rib B. A (in ² /in)	0.14	0.154		0.295	0.279		0.14	0.154		0.295	0.279		0.19	0.193		0.31	0.35			
Relative Rib Area	0.051	0.056		0.067	0.063		0.051	0.056		0.067	0.063		0.069	0.07		0.07	0.08			
Rib Bearing	0.233	0.256		0.189	0.179		0.233	0.256		0.189	0.179		0.317	0.321		0.2	0.22			
Area Ratio (1/in)																				
Measured Rib - Face Angle	46	51		48	44		46	51		48	44		44	49		45	53		51	
Meas. Coat Thick.	-	9.052		-	9.221		-	9.052		-	9.221		-	22.654		-	15.5		26.097	
Std.Dev. Coat. Thickness	-	1.916		-	2.334		-	1.916		-	2.334		-	5.4515		-	4.43		9.219	

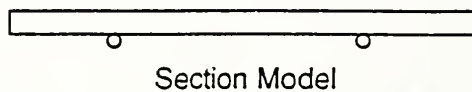
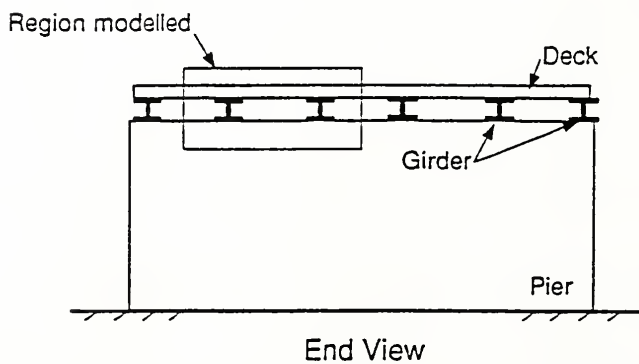
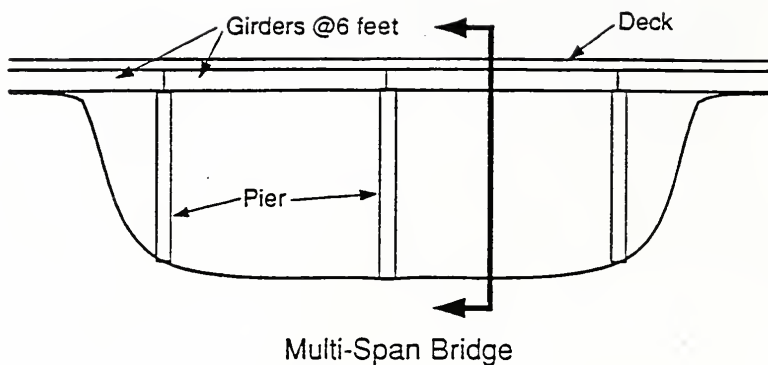
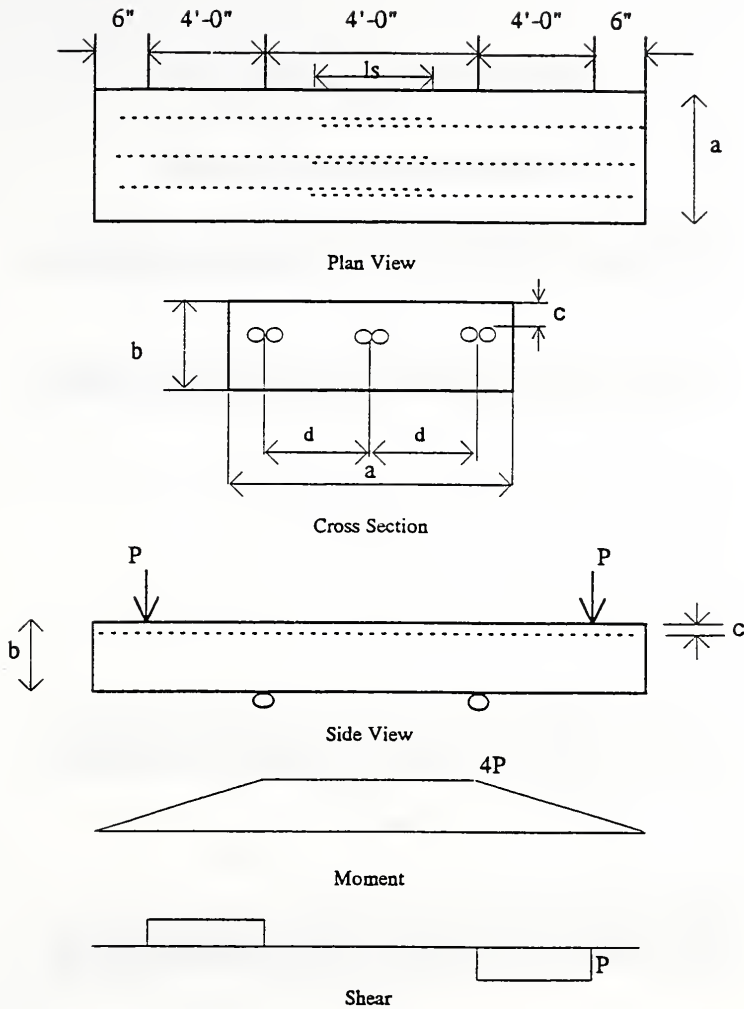


Figure 3.1 Evolution of Test Specimen



Specimen	Bar Size	a (in.)	b (in.)	c (in.)	d (in.)	Stirrup
Type A	# 7	24	8	2.5	6.5	# 3 @ 6 in.
Type B	# 11	28	12	2.5	8	# 3 @ 6 in.

Figure 3.2. Test Specimen and Loading Arrangement

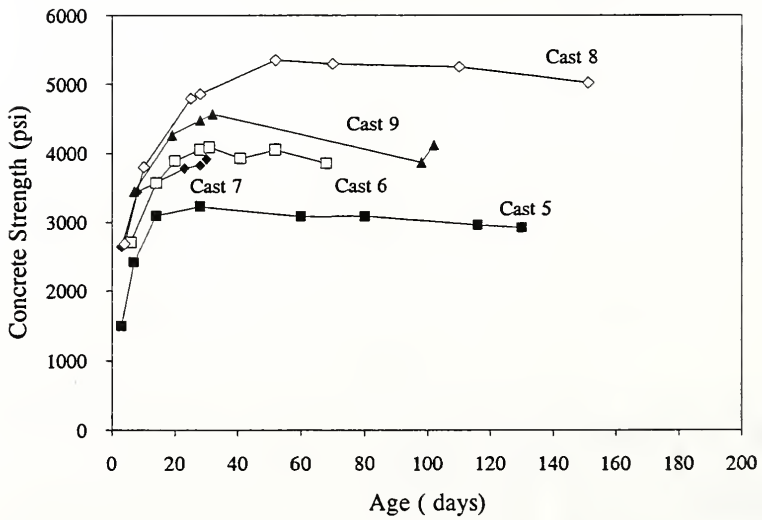
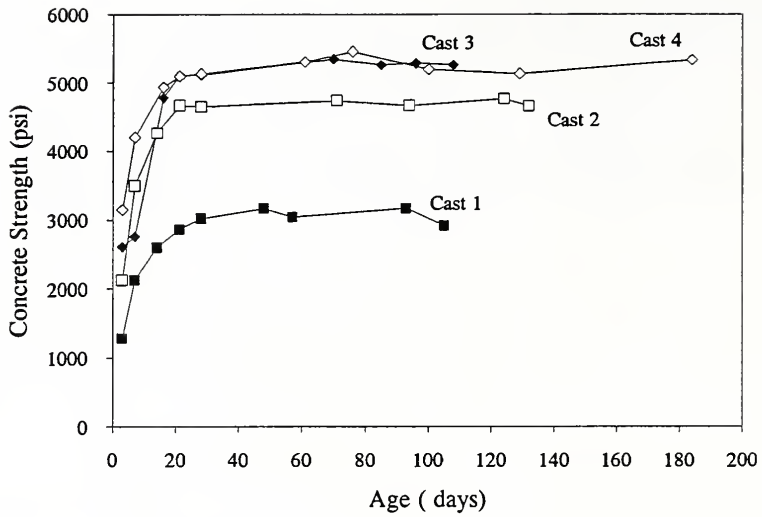


Figure 3.3 Concrete Strength Curves

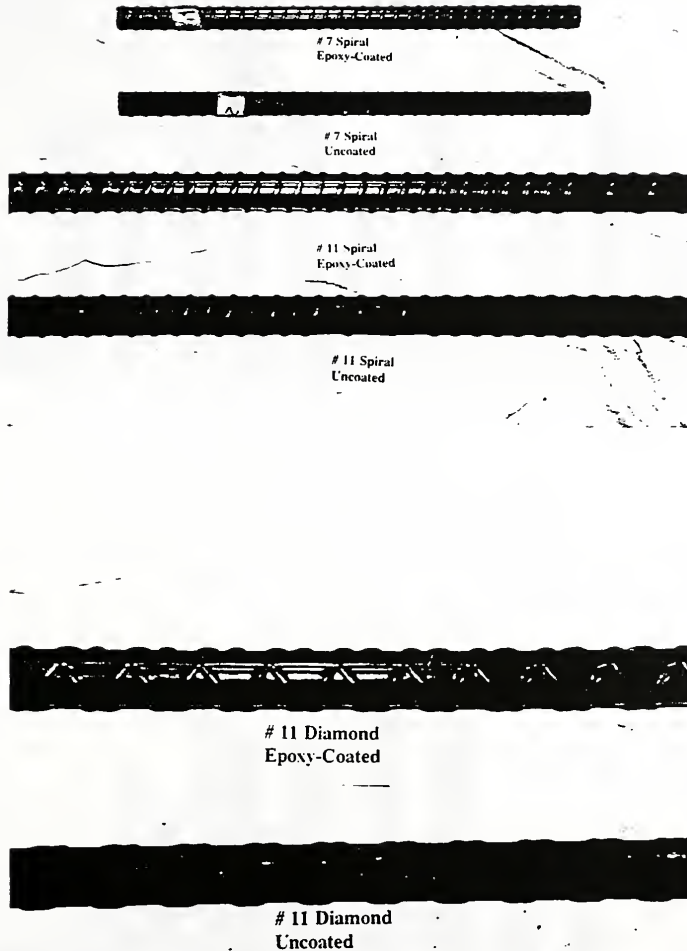


Figure 3.4 Reinforcement

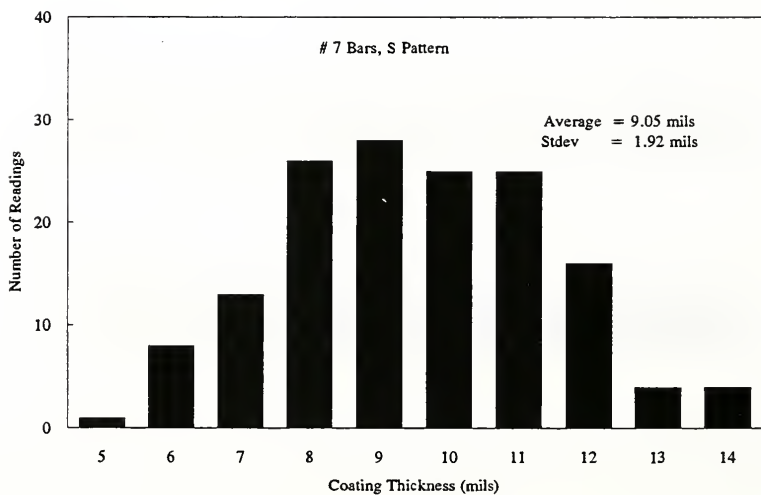
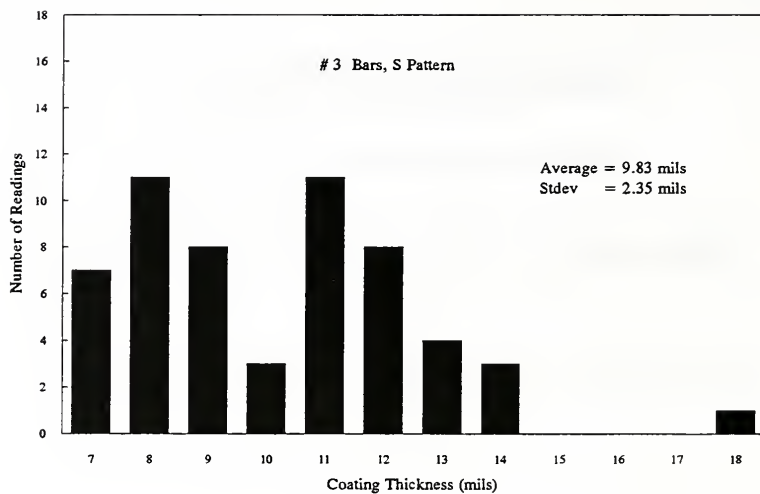


Figure 3.5 Measured Epoxy Coating Thickness

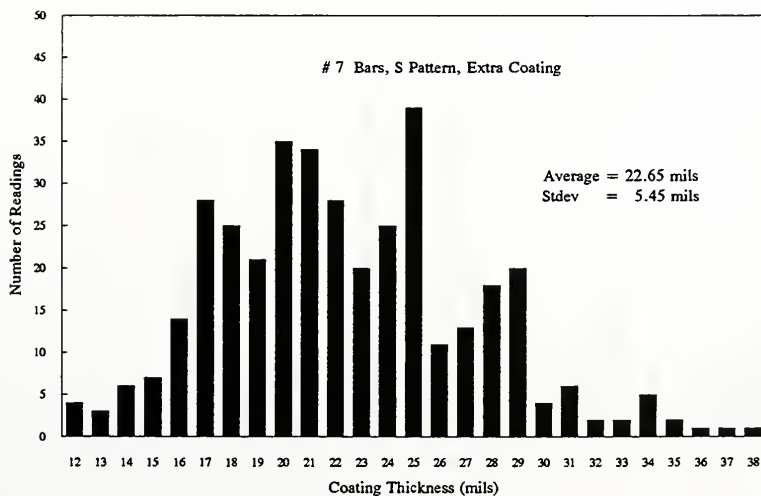
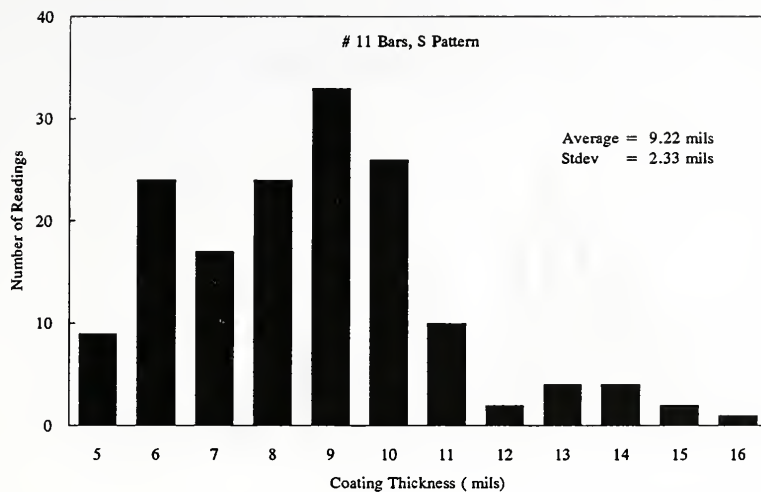


Figure 3.5 (Continued)

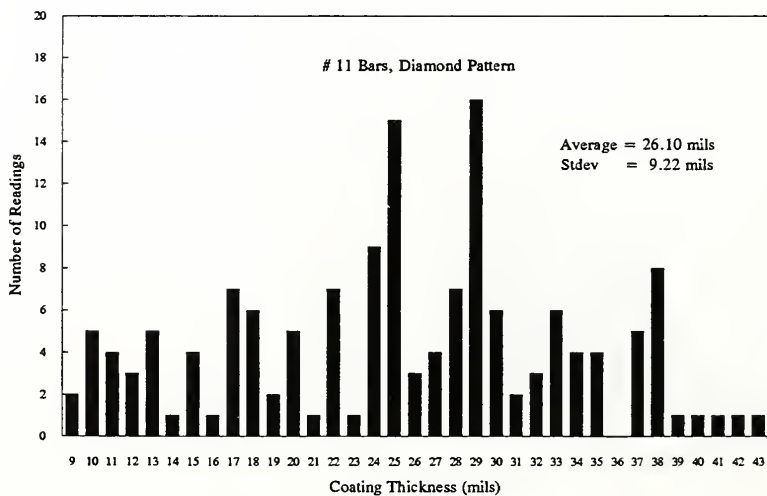
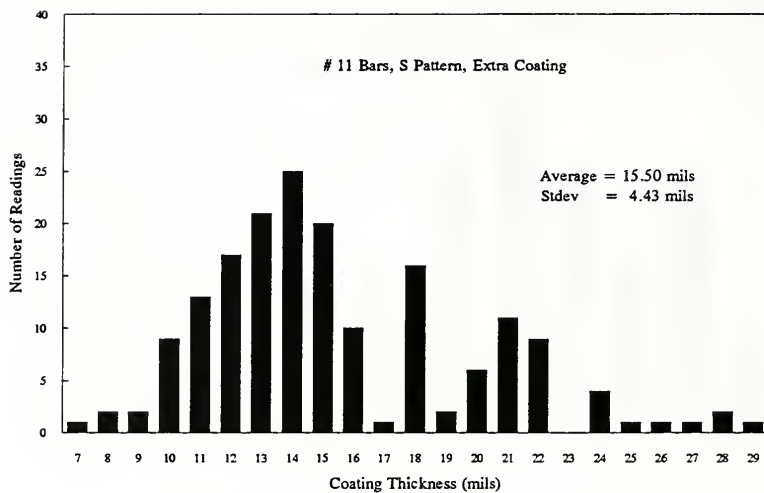


Figure 3.5 (Continued)

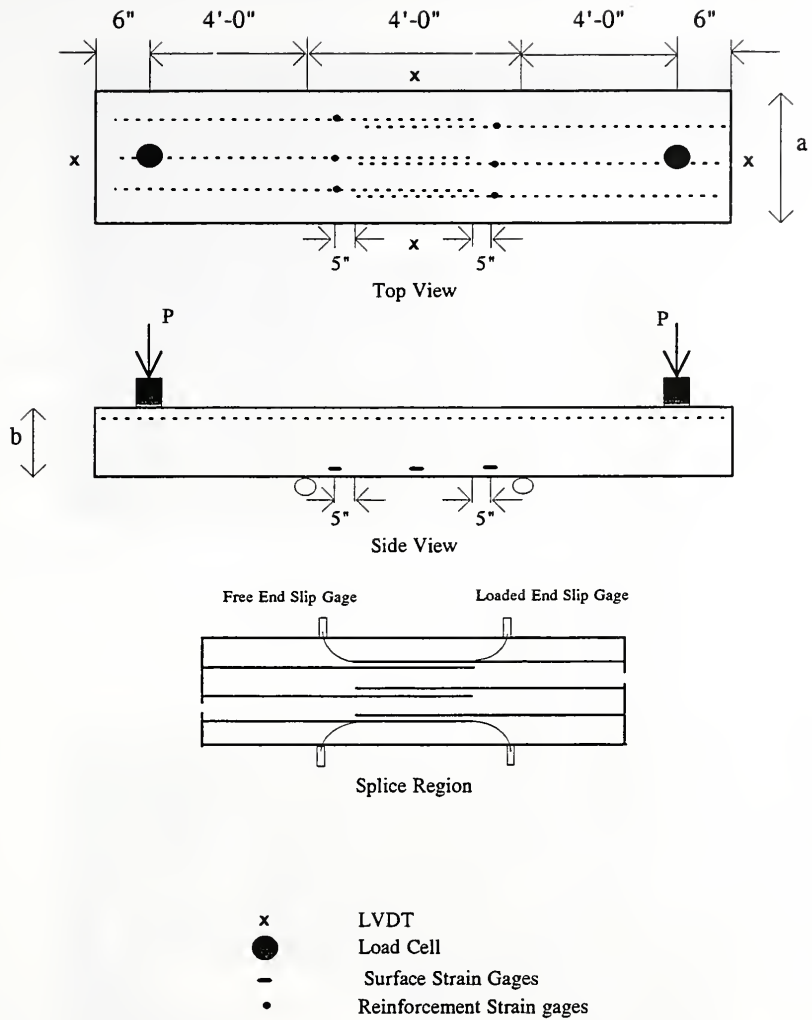


Figure 3.6 Instrumentation

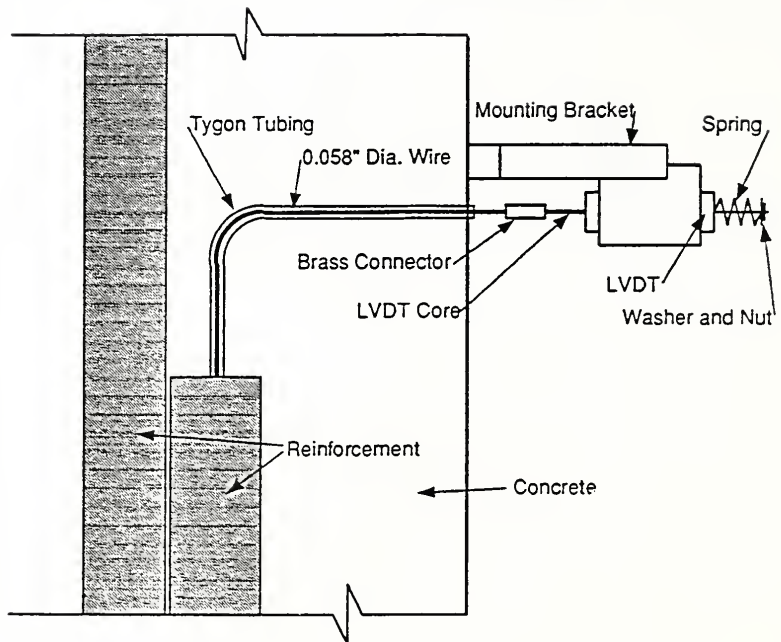


Figure 3.7 Detail of Slip Gage

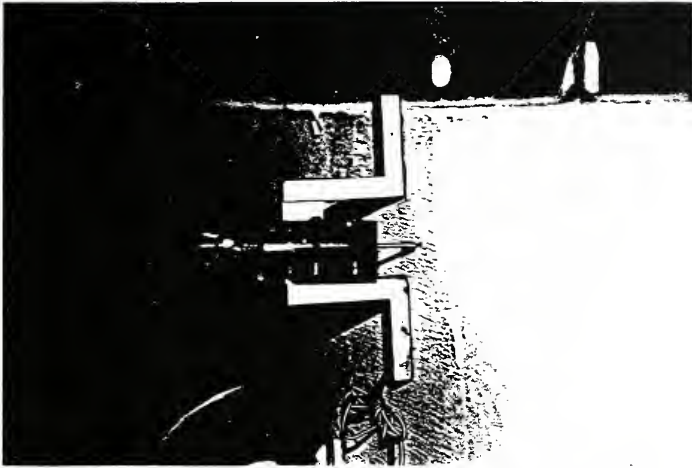


Figure 3.8 Mounted Slip Gage

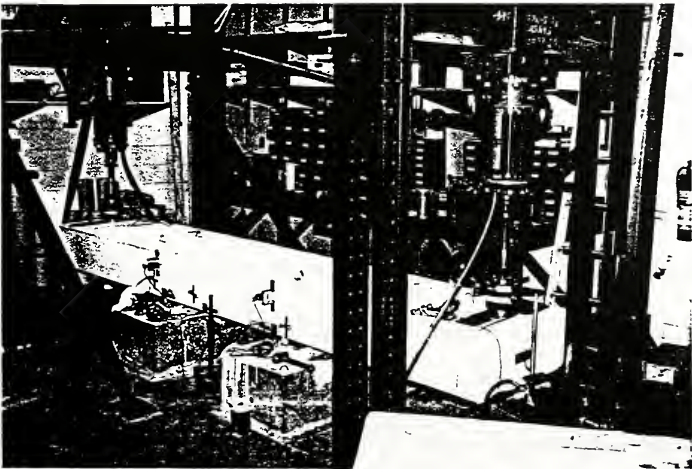


Figure 3.9 Specimen Prepared for Testing

CHAPTER 4 FINDING FROM LABORATORY PHASE

4.1 Introduction

This chapter presents the salient experimental findings from the laboratory phase of this study. The findings are reported in the areas of deflection, cracking, and bond strength. A detailed report on the experimental data gathered in this study can be found in reference [18].

4.2 Deflections

Deflections at each end and at the midspan of the specimens were obtained at each static loading cycle. Analysis of the cyclic load-deflection behavior was carried out for various loading levels and the effect of repeated loading is also discussed. Comparison of deflection data at the splitting load and the near failure are also made. The effect of deformation pattern and coating-thickness is also investigated.

4.2.1 Cyclic Load-Deflection Behavior

A typical cyclic load-deflection curve is shown in Figures 4.1 and 4.2 for the specimens tested. Figure 4.3 and 4.4 show load-deflection curves for specimens with single cycle load testing (static loading test) and hence are considered as the failure cycle. For both types of specimens, the largest permanent deformation due to cracking occurred during the first loading cycle, followed by a gradual increment in total deflection during subsequent loading cycles. For Type A specimens, except for series 7241 (see Figure 4.5), those reinforced with epoxy-coated reinforcement exhibited a

larger margin of permanent deformation due to cracking between the first and second loading cycles compared to specimens with uncoated steel. Accordingly, for the subsequent loading cycles, specimens with epoxy-coated reinforcement had larger deflections than specimens with uncoated steel. The total deflection is the sum of downward movement at the end and upward movement at midspan of the specimens. For Type B specimens, the difference in total deflection between specimens with epoxy-coated reinforcement and specimens containing uncoated steel is relatively small compared to Type A specimens. The load-deflection curves also indicate that compared to specimen with epoxy-coated reinforcement, the uncoated specimens fail at a substantially higher load level and hence at a larger failure or near failure deformation.

To compare the cyclic load-deflection behavior of specimens containing epoxy-coated reinforcement and specimens with uncoated steel, the average end deflections and average total deflections for various load levels and number of cycles are used as shown in Tables 4.1 through 4.16. For Type A specimens, the load levels considered are 2 kips, 3.5 kips, and the peak repeated load for corresponding beams. Similarly, the load levels selected for Type B specimens are 6 k, 16.7 k, and the peak repeated load. The loading cycles chosen are 2, 100,000, 450,000, and 1,000,000 cycles for all specimens. The numerical values of end and total deflection and the corresponding Epoxy/Uncoated or E/U ratios for Type A specimens at 2 kips, 3.5 kips, and peak repeated load are presented in Tables 4.1 through 4.3. Likewise, the average end and average total deflection and its E/U ratios for type B specimens at 6 k, 16.7 k, and

repeated load are presented in Tables 4.7 through 4.12. The statistical results of end and total deflections, and E/U ratios from the previous mentioned tables are summarized in Tables 4.13 through 4.16. The test results are presented in the following sections.

4.2.1.1 Type A specimens, Load Level $P = 2$ kips

Based on the average of all deflection values, the E/U ratios of end deflections were 1.064 for the 2nd cycle, 1.054 for 100,000th, 1.051 for the 450,000th, and 1.031 for the 1,000,000th. For total deflection, these ratios were 1.062, 1.058, 1.063, and 1.036. Based on an average of the individual E/U ratios, the average E/U ratios for average end deflection at 2 kips during the 1st, 100,000th, 450,000, and 1,000,000th cycle were 1.061, 1.051, 1.050, and 1.044. For total deflection, these ratios were 1.059, 1.055, 1.066, and 1.046.

4.2.1.2 Type A specimens, Load Level $P = 3.5$ kips

Based on the average of all deflection values, the E/U ratios of end deflections were 1.054 for the 2nd cycle, 1.049 for 100,000th, 1.043 for the 450,000th, and 1.019 for the 1,000,000th. For total deflection, these ratios were 1.051, 1.049, 1.052, and 1.023. Based on an average of the individual E/U ratios, the average E/U ratios for average end deflection at 3.5 kips during the 1st, 100,000th, 450,000, and 1,000,000th cycle were 1.052, 1.048, 1.042, and 1.033. For total deflection, these ratios were 1.049, 1.047, 1.050, and 1.034.

4.2.1.3 Type A specimens, Load Level P = Peak Repeated Load

Based on the average of all deflection values, the E/U ratios of end deflections were 1.052 for the 2nd cycle, 1.048 for 100,000th, 1.044 for the 450,000th, and 0.981 for the 1,000,000th. cycle. For total deflection, these ratios were 1.050, 1.049, 1.052, and 0.984. Based on an average of the individual E/U ratios, the average E/U ratios for average end deflection at peak repeating load during the 1st, 100,000th, 450,000, and 1,000,000th cycle were 1.048, 1.045, 1.039, and 1.029. For total deflection, these average E/U ratios were 1.046, 1.045, 1.046, and 1.031.

4.2.1.4 Type B specimens, Load Level P = 6 kips

Based on the average of all deflection values, the E/U ratios of end deflections were 1.062 for the 2nd cycle, 1.014 for 100,000th cycle, 0.975 for the 450,000th cycle, and 0.980 for the 1,000,000th cycle. For total deflection, these ratios were 1.058, 0.998, 0.971, and 0.976. Based on an average of the individual E/U ratios, the average E/U ratios for average end deflection at 6 kips during the 1st, 100,000th, 450,000, and 1,000,000th cycle were 1.063, 1.025, 0.998 and 1.019. For total deflection, these ratios were 1.059, 1.010, 0.998, and 1.022.

4.2.1.5 Type B specimens, Load Level P = 16.7 kips

Based on the average of all deflection values, the E/U ratios of end deflections were 1.045 for the 2nd cycle, 1.005 for 100,000th cycle, 0.990 for the 450,000th cycle, and 0.989 for the 1,000,000th cycle. For total deflection, these ratios were 1.044, 0.996,

0.984, and 0.983. Based on an average of the individual E/U ratios, the average E/U ratios for average end deflection at 16.7 kips during the 1st cycle, 100,000th cycle, 450,000th cycle, and 1,000,000th cycle were 1.045, 1.014, 1.007, and 1.017. For total deflection, these ratios were 1.043, 1.006, 1.002, and 1.014.

4.2.1.6 Type B specimens, Load Level P = Peak Repeated Load

Based on the average of all deflection values, the E/U ratios of end deflections were 1.045 for the 2nd cycle, 1.000 for 100,000th cycle, 0.976 for the 450,000th cycle, and 0.975 for the 1,000,000th cycle. The E/U ratios for total deflections were 1.043, .992, 0.970, and 0.969. Based on an average of the individual E/U ratios, the average E/U ratios for average end deflection at peak repeating load during the 1st, 100,000th, 450,000, and 1,000,000th cycle were 1.044, 1.017, 1.008, and 1.016. For total deflection, the average E/U ratios were 1.042, 1.010, 1.003, and 1.013.

Tables 4.13 through 4.16 give the summaries of the statistical results as computed in Tables 4.1 through 4.12. For Type A specimens, the average values for E/U ratios of end deflections based on average deflection values for various load levels considered (see Table 4.13) were 1.057 for the 2nd cycle, 1.050 for the 100,000th cycle, 1.046 for 450,000th cycle, and 1.010 for 1,000,000th cycle. For total deflection, these ratios were 1.054, 1.052, 1.055, and 1.015. As shown in Table 4.14, the average values for E/U ratios of end deflections based on individual E/U ratios for various load levels considered were 1.054 for the 2nd cycle, 1.048 for the 100,000th cycle, 1.044 for 450,000th cycle, and 1.035 for 1,000,000th cycle. For total deflection, these ratios were 1.051, 1.049, 1.052,

and 1.037.

Table 4.15 and Table 4.16 summarize the statistical results of end and total deflections for Type B specimens for various load levels as computed in Tables 4.7 through 4.12. The average values for E/U ratios of end deflections based on average deflection values (Table 4.15) for various load levels considered were 1.051 for the 2nd cycle, 1.006 for the 100,000th cycle, 0.980 for 450,000th cycle, and 0.982 for 1,000,000th cycle. For total deflection, these ratios were 1.048, 0.995, 0.975, and 0.976. The average values for E/U ratios of end deflections based on individual E/U ratios (Table 4.16) for various load levels considered were 1.050 for the 2nd cycle, 1.019 for the 100,000th cycle, 1.004 for 450,000th cycle, and 1.018 for 1,000,000th cycle. For total deflection, these ratios were 1.048, 1.009, 1.001, and 1.016.

The average E/U ratios of both specimen types indicate that specimens with epoxy-coated reinforcement have larger deflections, but the differences decrease with repeated loading.

4.2.2 Near Failure and Post-Splitting Deflections

Tables 4.17 and 4.19 show the total deflection at splitting and failure (or just prior to failure). Also shown is the difference between the splitting and failure load and deflections. The E/U ratios of load and deflection are presented in Tables 4.18 and 20. The ratios of post-splitting versus splitting loads are presented in Table 4.21.

For Type A specimens, the average deflection at which splitting cracks were first observed was 1.519 inches in the specimens with uncoated bars, and 1.283 inches for

specimens with epoxy-coated reinforcement. The E/U ratios for splitting deflections was 0.845. The average total deflection near failure was 1.589 inches for specimens with uncoated reinforcement, and 1.302 inches for specimens with coated steels. The corresponding E/U ratio was 0.819. The difference between the average failure deflection and average splitting deflection, namely, average post-splitting deflection, for specimens with uncoated reinforcement was 0.070 inches. On the other hand, the difference was 0.019 inches for specimens with epoxy-coated reinforcement. The E/U ratio of 0.271 indicates that specimens with uncoated bars are able to sustain 3.7 times more deformation after the first splitting crack than specimens with epoxy-coated bars prior to failure. In terms of the load, the post-splitting load increase was 4.36% for specimens with uncoated steel, and 2.02% for specimens with epoxy-coated reinforcement. In other words, specimens with uncoated steel can take a 2.16 times larger post-splitting load relative to its splitting load than specimens with epoxy-coated steel.

For Type B specimens, the average splitting deflection for specimens with uncoated bars was 0.689 inches. The deflection was 0.623 inches for specimens with epoxy-coated reinforcement. The E/U ratio was 0.904. The average total deflection near failure was 1.042 inches for specimens with uncoated reinforcement and 0.761 inches for specimens with epoxy-coated reinforcement. The corresponding E/U ratio was 0.730. The average post-splitting deflection for specimens with uncoated reinforcement was 0.353 inches, and 0.138 inches for specimens with epoxy-coated reinforcement. The E/U ratio was 0.391. In other words, the Type B specimens with uncoated bars were able to sustain 2.6 times more deformation after the first split than specimens with epoxy-coated bars

before failure. In terms of loads, the relative ratio of the ratio of post-splitting load to splitting load of specimens with uncoated steel was 42.48%, and 17.95% for specimens with epoxy-coated reinforcement. This means specimens with uncoated steel can take 2.37 times larger post-splitting load relative to the splitting load than specimens with epoxy-coated steel.

4.2.3 Effect of Peak Stress

Table 4.22 contains the evaluation of the effect of peak stress. The upper bound stress used in the repeated loading phase, or peak stress, significantly affects the maximum deflections at peak repeated load. Obviously, specimens subjected to a higher peak stress have larger maximum deflections. For Type A specimens, the average of total deflection at peak repeated load for specimens with a peak stress of 24 ksi was 0.662 inches for either coated and uncoated specimens. For specimens with a peak stress of 36 ksi, the maximum total deflections were 1.036 inches (uncoated), and 1.085 inches (coated). For specimens with a peak stress of 30 ksi, the maximum total deflections were 0.941 inches (uncoated) and 1.066 inches (coated). For uncoated specimens, the ratios of the average maximum total deflection for specimens with peak stress equal to 30 ksi and 36 ksi to specimens with a peak stress of 24 ksi were about 1.42 and 1.56 respectively. For coated specimens, these ratios were 1.61 and 1.64. For Type B specimens, the average total deflection at peak repeated load for specimens with a peak stress of 24 ksi was 0.436 inches for uncoated specimens and 0.455 inches for coated specimens. The average total deflections at peak repeated load for specimens with a peak stress of 30 ksi

were 0.544 inches for uncoated specimens and 0.567 for coated specimens. The relative deflections were 1.248 (uncoated) and 1.246 (coated).

4.2.4 Effect of Stress Range

The incremental increase in deflection caused by cycling is influenced by the stress range applied. Table 4.23 shows the evaluation of the effect of stress range. The following is a presentation of test results taken at peak repeated load level.

For Type A specimens with uncoated bars, the average increase in total deflection from 2nd cycle to 1 millionth cycle with an 8.74 ksi stress range was 0.116 inches and 0.182 inches with a stress range of 15 ksi. For type A specimens with epoxy-coated bars the increase with an 8.74 ksi stress range was 0.136 inches, for the 15 ksi stress range the increase was 0.162 inches.

For Type B specimens, the increase in total deflection from 2nd cycle to 1 millionth cycle for uncoated specimens with a stress range of 8.74 ksi was 0.083 inches, for the 15 ksi stress range the increase was 0.122 inches. For specimens with epoxy-coated bars, the increase was 0.074 inches for a stress range of 8.74 ksi and 0.075 inches for a stress range of 15 ksi.

For a set of directly comparable specimens, for example: U7361 versus U7362; U11241 and U11242 vs. U11243 etc., a larger increase in deflection due to cycling is observed with a 15 ksi stress range than with an 8.74 ksi stress range. Although the previous observation was made for peak repeated load level, similar behavior is also observed for other loading levels.

4.2.5 Effect of Coating Thickness and Deformation Pattern

Table 4.24 shows the evaluation of effects of coating thickness and deformation pattern. For Type A specimens, the splitting and failure load, and the corresponding deflections were lower for specimens with extra thickness of coating compared to specimens with uncoated steel. The splitting and failure loads of series 7361 and 7362 with epoxy-coated steel were 6.05 and 6.05 kips respectively, the corresponding deflections were 1.350 at both splitting and failure. For series 736SX, the splitting and failure loads were both 5.50 kips, the corresponding deflections were both 1.320 inches. For Type B Specimens, the reverse is true, specimens with extra thickness of coating had larger splitting and failure loads and larger deflection. The splitting and failure loads of series 11301 and 11302 with epoxy-coated steel were 22.00 kips and 29.31 kips respectively, and 23.00 and 32.00 kips for specimens with extra thickness of coating. The splitting and failure deflections for series 11301 and 11302 were 0.623 inches and 0.851 inches for specimens with coated steel, and 0.641 inches and 0.849 inches for series 1130SX with extra thickness of coating.

Specimens with a diamond deformation pattern, series 1130DX, with coated or uncoated steels; show larger cyclic deflection compared to specimens with spiral deformation pattern (series 1130SX). The splitting and failure loads as well as splitting and failure deflections were lower compared to those of specimens with a spiral deformation pattern.

4.2.6 Discussion

The typical cyclic load-deflection (Figure 4.1) and the typical deflection versus number of cycles plot for various load levels (Figures 4.6 and 4.7) show the increase in deflection as the number of cycles increases. The greatest rate of increase occurred during the first 200,000 cycles and became somewhat steady beyond this point. Specimens containing epoxy-coated reinforcement had larger deflections than those of specimens with uncoated bars. However, the increase in deflection with cycling was larger in specimens with uncoated reinforcement. In Type A specimens, it was found that the deflections of specimens with epoxy-coated reinforcement initially were 5.1% larger but the difference was reduced to 3.7% after 1,000,000 cycles. For Type B specimens, initially deflections of specimens with epoxy-coated reinforcement were 4.8% larger but reduced to 1.6% after 1,000,000 cycles. These results indicate that in specimens with uncoated steel the deflections increase with a more rapid rate with the cycling. Although cycling was limited to a maximum of 1,000,000 cycles, it has been reported in the previous research by Cleary and Ramirez [11] that further cycling will continue to reduce the differences in deflection between specimens with uncoated steel and specimens containing epoxy-coated reinforcement. It has also been reported that initially there is a relatively larger upward movement at the centerline of the uncoated specimens as reflected in the higher E/U ratio (1.4%) for average end deflection compared to total deflection. Based on this observation, it has been speculated that this may be a reflection of the larger number of cracks found with uncoated bars allowing more rotation in this region. Results of current tests show that E/U ratios of average end deflection and average

total deflection only differ by a maximum of 0.4%, most are less than 0.1%. Furthermore, during the cycling, in many cases, the E/U ratio of average end deflections was found to be even higher than that of total deflections. So, more cracks do not necessarily lead to more rotation, instead, it seems that the total crack width is a better indicator of the amount of rotation.

The peak stress influences the deflections of the members. Since higher loads are required to produce a higher peak stress, it is likely that the permanent deformation after the 1st loading cycle will be larger. This permanent deformation will be carried over to influence the magnitude of deformation of subsequent repeated loading. There is no clear indication that peak stress influences the E/U ratios.

The stress range influences the changes in deflection with cycling in both specimens with uncoated steel and specimens with epoxy-coated reinforcement. Larger stress range resulted in larger increase in deflection throughout cycling. Because more energy is required to produce a larger stress range, the internal damage caused by the cycling obviously will be more detrimental. As in the case of the influence of peak stress, no clear influence of stress range on E/U ratio has been found.

Peak stress influences the splitting and failure deflections. For specimens with uncoated steel, lower peak stress resulted in smaller splitting as well as failure deflections. For specimens with epoxy-coated reinforcement, no inferences can be made.

Stress range also influences the splitting and failure deflections. Results of the comparison shown in Table 4.23 indicate that lower stress range tends to give smaller splitting deflections for either specimens with uncoated bars and specimens with epoxy-

coated bars. In terms of the failure deflection, the same result holds true for specimens with uncoated steel. However, for specimens with epoxy-coated bars, the influence of stress range on failure deflection is not clear.

Table 4.24 shows the evaluation of extra-thickness coating and deformation pattern. For Type A specimens, the specimen with extra thickness of coating had a larger total deflection. For Type B specimens, the deflections of the specimen with extra-coating thickness and normal coating thickness are nearly the same. One is reluctant to make inferences on the effect of the deformation pattern due to the very limited data on the diamond deformation pattern. However, the limited results may provide an indication that members containing bars with a diamond deformation pattern have lower splitting and failure loads and have lower splitting and failure deflections.

4.2.7 Summary

For Type A specimens, the total deflection of specimens with epoxy-coated bars exceeded that of specimens with uncoated reinforcement by 5.4% at the 2nd load cycle and reduced to 3.5% after 1 million cycles. Repeated loading increases the deflections for both specimens reinforced with uncoated steel and those with coated bars. However, the changes were larger in specimens with uncoated reinforcement. The largest change in deflection occurred in the first 200,000 cycles.

Specimens with uncoated steel have increased ductility in the splitting mode of failure. Observation of splitting behavior indicates that, compared to specimens with epoxy-coated steel, specimens with uncoated steel are able to carry as much as twice the

additional load after splitting. This indicates a more brittle failure mode in specimens with epoxy-coated reinforcement.

The peak stress significantly affects the maximum deflections at peak repeated load. Specimens with higher peak stress produce larger maximum deflection. Peak stress also influences the splitting and failure deflections for uncoated specimens. For specimens with uncoated steel, lower peak stress resulted in smaller splitting as well as failure deflections. No conclusive comment on the effect of peak stress on splitting and failure deflection can be made for specimens with epoxy-coated reinforcement.

Higher stress range resulted in larger splitting deflections and larger increase in deflection between the cycling for either specimens with uncoated bars and specimens with epoxy-coated bars. Higher stress range also resulted in higher failure deflection for uncoated specimens. However, for specimens with epoxy-coated bars, the influence of stress range on failure deflection is not clear. No clear indication of the effect of peak stress and stress range on E/U ratios of deflection was found.

Comparison based on the very limited data on the effect of extra thick coatings indicated that members containing bars with a diamond deformation pattern (series 1130DX) had larger cyclic deflection compared to specimens with a spiral deformation pattern (series 1130SX). Also, the splitting and failure loads as well as splitting and failure deflections were lower compared to those of specimens with a spiral deformation pattern.

4.3 Cracking

In this section, comparisons of the cracking performance of members with epoxy-coated steel and members with uncoated steel subjected to fatigue loading are made. Areas considered include crack patterns, flexural and splitting cracking loads, failure loads, number of cracks, and crack widths. The following sections summarize of the data related to cracking for all specimens tested.

4.3.1 Flexural and Splitting Crack Patterns

A typical crack pattern for Type A and Type B specimens is shown in Figures 4.8 and 4.9. There are mainly two types of cracks formed during the tests, flexural cracks and splitting cracks. Flexural cracks, formed in the transverse direction of the specimens, usually appear during the first static loading cycle, occasionally one or two cracks form during the 2nd static cycle. Splitting cracks occur over the splice in a direction parallel to the longitudinal reinforcement. The peak repeated loads were selected to be below the predicted splitting load. Therefore splitting cracks were not expected to form during the load cycling or static loading between cycling. That was the case for most of the specimens, except for specimens E7362 and E11303; the splitting cracks formed earlier during the cyclic loading, and eventually led to failure during fatigue loading.

As can be observed from the crack patterns recorded, the first flexural cracks randomly formed in the constant moment region. Due to stress concentration, two flexural cracks were generally formed at or close to each end of the splice. The first splitting cracks were formed in the final failure loading cycle. Further loading caused the

formation of new cracks and gradual propagation of the previous splitting cracks.

Although the trend of splitting crack pattern in the splice region for both Type A and Type B specimens was similar, however, there were a large number of splitting cracks in Type B specimens. This is because the post-splitting loads for Type B specimens were higher so more splitting cracks were formed before failure.

4.3.2 Flexural Crack Patterns at Failure

Additional flexural cracks were formed when specimens were loaded beyond the peak repeated load during the failure cycle. Table 5.1 shows comparisons of the number of cracks present at failure. As indicated by the E/U ratios, Type B specimens with uncoated bars had more cracks than those with epoxy-coated bars before and after failure except for cracks outside the splice. At failure, for Type A specimens, in four cases the uncoated specimens had more flexural cracks, in two cases had the same number of flexural cracks, and in two cases uncoated specimens had fewer flexural cracks. For Type B specimens, in two cases the uncoated specimens had more flexural cracks, in five cases had the same number of flexural cracks, and in one case uncoated specimens had fewer flexural cracks. In the constant moment region, the E/U ratio of total number of cracks at failure was 0.945 for Type A specimens, and 0.930 for Type B specimens.

4.3.3 Splitting Crack Patterns at Failure

Figure 4.7 and 4.8 show the splitting crack patterns in the specimens. The first

splitting crack typically occurred at the end of one of the outer splices. Further loading after first splitting led to the extension of existing splitting cracks and formation of new splitting cracks. Compared to Type A specimens, Type B specimens had more splitting cracks at failure. These cracks tended to be shorter than those found in Type A specimens.

4.3.4 Cracking Load

Table 4.26 presents a comparison of the flexural cracking loads as well as splitting cracking loads for each of the specimens tested under fatigue loading. Comparison is made with the E/U ratio of average cracking load and the average of the individual E/U ratios of each specimen.

For Type A specimens, in four cases, the flexural cracking load was greater for specimens with uncoated bars, and in three cases it was lower for specimens with epoxy-coated bars. For Type B specimens, in three cases, the flexural cracking load was greater for specimens with uncoated bars, in three cases it was lower for specimens with epoxy-coated bars, and in two cases the flexural cracking loads were the same. The E/U ratio based on flexural cracking loads was found to be 0.872 for Type A specimens, and 0.898 for Type B Specimens. The average of individual E/U ratio was 0.913 for Type A specimens, and 0.941 for and Type B specimens. The difference in flexural cracking load between specimens with epoxy-coated bars and specimens with uncoated bars was insignificant.

4.3.5 Splitting Load

Test results indicate that the majority of the specimens with epoxy-coated bars show signs of splitting at a lower load level compared to specimens with uncoated bars. For Type A specimens, six out of seven series of specimens had a lower splitting load level than that of uncoated specimens; in one series the splitting loads were the same for either type of steel. For Type B specimens, six series had a lower splitting load for specimens with epoxy-coated bars, and in two series the splitting load was higher for specimens with epoxy-coated bars. The average E/U ratio of splitting load was 0.795 for Type A specimens, and 0.899 for Type B specimens. Based on the individual E/U ratio, these values were 0.802 and 0.914. These values indicate a reduction of 20 % in splitting load for Type A specimens with epoxy-coated bars, and 10 % for Type B specimens with epoxy-coated bars.

4.3.6 Crack Widths

A comparison of the performance of members with epoxy-coated steel and members with uncoated steel is made with the total crack width and the average crack width. During each static loading cycle, flexural crack widths were measured at three locations along each crack in the constant moment region.

Comparisons of the crack width data for each type of specimens are made in two ways. First, crack width data at three different load levels are considered. E/U ratios are then computed from the average values of either total crack width or average crack width. The average values of the E/U ratios from the result of these three load levels are then

used as representative values for comparison purposes. Second, for three different load levels selected; E/U ratios are computed as the average values of the individual E/U ratios of each set of epoxy-coated and uncoated specimens for either total crack width or average crack width. The average values of these E/U ratios are then used as representative values for comparison purposes.

4.3.6.1 Crack Width in the Constant Moment Region

For Type A specimens, the load levels chosen for this investigation were $P=2$ kips, $P=3.5$ kips, and $P=\text{peak repeated load}$. Results of the E/U ratio computations are presented in Tables 4.27 through 4.44. For Type B specimens, the load levels considered are $P=6$ kips, $P=16$ kips, and $P=\text{peak repeated load}$. Results of the E/U ratio computation are presented in Tables 4.45 through 4.62. Tables 4.63 through 4.74 are summaries of statistics and representative values for the E/U ratio of all the comparisons that have been made for both types of specimens.

Tables 4.63, 4.64, 4.69 and 4.70 show the statistics and the representative values of E/U ratio for either total crack width and average crack width in the constant moment region for Type A and Type B specimens. For Type A specimens, based on the average of the total crack width, the E/U ratios at the 2nd, 100,000th, 450,000th, and 1,000,000th cycle of load were found to be 1.063, 0.957, 0.971, and 0.988. These values were 1.263, 1.228, 1.125, and 1.134 for Type B specimens. Based on the average of the individual E/U ratios of total crack width, the values were 1.080, 1.004, 1.020, and 1.059 for Type A specimens. For Type B specimens, these values were 1.270, 1.246, 1.200, and 1.221.

Although there were some fluctuations of the E/U ratios, the E/U ratios tend to decrease with cycling which indicates that the differences in total crack width between members with epoxy-coated steel and members with uncoated steel were reduced with cycling. Investigation of the E/U ratios based on individual E/U ratio reveals that the widths of the individual cracks were larger for members with epoxy-coated steel. This is indicated by E/U ratios greater than 1. For Type A specimens, based on the average values of average crack width, the E/U ratios at the 2nd, 100,000th, 450,000th, and 1,000,000th cycle of load were 1.225, 1.105, 1.126 and 1.063. These values were 1.296, 1.246, 1.212, and 1.187 for Type B specimens. Based on the individual E/U ratio of average crack width, the average E/U ratios values were 1.254, 1.176, 1.199, and 1.184 for Type A specimens. For Type B specimens, these values were 1.328, 1.254, 1.243, and 1.225. Again, the differences in total crack width between members with epoxy-coated steel and members with uncoated steel were reduced with cycling.

4.3.6.2 Crack Widths in the Constant Moment Region Outside the Splice

Tables 4.65, 4.66, 4.71, and 4.72 show the statistics and the representative values of E/U ratios for either total crack width or average crack width in the constant moment region outside the splice for both type specimens.

For Type A specimens, based on the average of total crack width, the E/U ratios at the 2nd, 100,000th, 450,000th, and 1,000,000th cycle of load were 1.131, 0.970, 1.004, and 1.054. These values were 1.552, 1.415, 1.257, and 1.232 for Type B specimens. Based on the average of the individual E/U ratios of total crack width, the values were

1.252, 1.130, 1.216, and 1.251 for Type A specimens. For Type B specimens, these values were 1.658, 1.416, 1.386, and 1.370. The trend of the E/U ratios is very similar to that of the crack widths in the constant moment area; the differences in total crack width between members with epoxy-coated steel and members with uncoated steel were reduced with cycling. Results of the E/U ratios based on individual E/U ratios also indicate that individual cracks of members with epoxy-coated steel were larger. For Type A specimens, based on the average values of average crack width, the E/U ratios at the 2nd, 100,000th, 450,000th, and 1,000,000th cycle of load were 1.220, 1.054, 1.071, and 0.904. These values were 1.449, 1.333, 1.332, and 1.277 for Type B specimens. Based on the average of the individual E/U ratios of average values of average crack width, the values were 1.252, 1.146, 1.199, and 1.023 for Type A specimens. For Type B specimens, these values were 1.487, 1.298, 1.296, and 1.261. Again, similar to results of crack width in the constant moment region, the differences in total crack width between members with epoxy-coated steel and members with uncoated steel were reduced with cycling.

4.3.6.3 Crack widths Inside the Splice

Tables 4.67, 4.68, 4.73 and 4.74 show the statistics and the representative values of the E/U ratio for either total crack width or average crack width inside the splice for Type A specimens and Type B specimens.

Results of E/U ratios of total crack width indicate that the crack widths of uncoated specimens were larger than epoxy-coated specimens for Type A specimens but were smaller for Type B specimens. However, results of E/U ratios of average crack

width show that the average crack widths of epoxy-coated specimens were larger for both Type A and Type B specimens. For Type A specimens, based on the average of total crack width, the E/U ratios at the 2nd, 100,000th, 450,000th, and 1,000,000th cycle of load were 0.904, 0.935, 0.983, and 0.849. These values were 1.209, 1.065, 1.045, and 1.060 for Type B specimens. The average of the individual E/U ratios of total crack width were 0.932, 0.961, 1.013, and 0.973 for Type A specimens. For Type B specimens, these values were 1.437, 1.408, 1.248, and 1.284. Based on the average values of average crack width, the E/U ratios for Type A specimens at the 2nd, 100,000th, 450,000th, and 1,000,000th cycle of load were found to be 1.249, 1.303, 1.321, and 1.070. These values were 1.273, 1.125, 1.119, and 1.095 for Type B specimens. Based on the average of the individual E/U ratios of average values of average crack width, the values were 1.271, 1.315, 1.284, and 1.228 for Type A specimens. For Type B specimens, these values were 1.298, 1.158, 1.221, and 1.187. Overall, repeated loading has the effect of reducing the differences in total and average crack width between members with epoxy-coated steel and members with uncoated steel.

4.3.7 Effect of Coating Thickness and Deformation Pattern

For Type A specimens, the crack widths inside the splice region were larger for specimens with extra thickness of coating (series 7361, 7362, 7363 versus 736SX). However, the crack widths were smaller for Type B specimens with bars of extra thickness of coating. This would seem to indicate that the extra coating thickness affects more smaller diameter bars.

Although there was only one data point on diamond pattern available, the total crack widths of the specimens with diamond deformation pattern (series 1130DX) were the largest for all the Type B specimens tested. This may be an indication that specimens with bars having a diamond deformation would have a larger crack width as the thickness of coating is increased.

4.3.8 Rate of Crack Opening

A typical graph of total crack width versus number of cycles is presented in Figure 4.10 and Figure 4.11. The plots include the three different load levels evaluated. The total crack width includes all cracks in the constant moment region. A detailed presentation of this behavior for all the specimens tested can be found in reference [18]. From this behavior it is observed that crack width increases with repeated loading. However; it is difficult to compare the rate of crack opening between specimens with epoxy-coated steel and specimens with uncoated steel. Comparison of the E/U ratio in the previous section provides an indication that the total crack widths of members with epoxy-coated bars were larger initially compared to members with uncoated steel, however; the differences were reduced with cycling.

4.3.9 Discussion

Research in the past [3,11,19,20,21] has shown that fewer but wider cracks have been found for members with epoxy-coated reinforcement. Results from current tests are in agreement with this finding. For both types of specimens, fewer flexural cracks were

found in epoxy-coated specimens either before or after failure for Type A specimens. In Type B specimens the total number of cracks before failure was nearly the same for both epoxy-coated and uncoated specimens.

The post-splitting load influences the pattern of splitting cracks. The post-splitting load is the load that can be further carried before failure after the first splitting crack is observed. A larger post-splitting load caused more splitting cracks to form. Generally, the post-splitting load for epoxy-coated specimens is smaller than that of uncoated specimens and hence there are fewer splitting cracks. Column 4 of Tables 4.17 and 4.19 contains the values of post splitting load, and the difference between failure load and splitting load, for Type A and Type B specimens respectively. For Type A specimens, the differences in splitting load between uncoated specimens and epoxy-coated specimens are small. Hence there are no significant differences in splitting crack patterns. For Type B specimens, the post splitting loads for either uncoated specimens and epoxy-coated specimens are relatively high. This resulted in more splitting cracks. The epoxy-coated specimens had relatively much lower post splitting loads than uncoated specimens, therefore fewer splitting cracks were formed before failure. Consequently, epoxy-coated specimens had simpler splitting crack patterns compared to those of uncoated specimens.

Cracking loads for epoxy-coated specimens were found to be lower than those of uncoated specimens. Cleary and Ramirez [11] reported values of 0.833 to 1.25 with an average of 0.986. In this study, based on the average value of individual E/U ratios, the E/U ratios of cracking loads for Type A specimens ranged from 0.5 to 1.111 with an average value of 0.924. For Type B specimens, the E/U ratios were 0.5 to 1.333 with an

average value of 0.941.

The combination of c/d_b and l_s/d_b seems to be a determining factor for the splitting load. Higher values of c/d_b and l_s/d_b would be beneficial in increasing the splitting load for epoxy-coated members. Table 4.76 shows the evaluation of these factors based on data from Cleary and current tests. It is observed from the Cleary's tests, that for the same c/d_b ratio, a larger value of l_s/d_b gave a higher E/U ratio (Case 3 versus Case 4). Comparing Case 2 and Case 3, the larger value of l_s/d_b did not give a higher E/U ratio because it has lower c/d_b ratio. On the other hand, comparison of Case 1 versus Case 2 shows that the larger l_s/d_b value gave a higher E/U ratio even though it has lower c/d_b ratio. Presumably both factors are controlling, there should be an optimum combination of c/d_b ratio and l_s/d_b ratio that gives the optimum splitting load.

Splice length also influences the post splitting load. For Type A specimens, the average post splitting load was 0.39 kips for uncoated members and 0.13 kips for epoxy-coated members. For Type B specimens, the average post splitting load was 11.03 kips for uncoated specimens and 4.09 kips for epoxy-coated specimens. Cleary and Ramirez reported the average post splitting load of 0.45 kips for uncoated members and 0.11 kips for epoxy-coated members with a 12 inch splice length. For 10 inch splice length the post-splitting loads were 0.064 kips for uncoated members and 0.147 kips for epoxy-coated members.

Cleary and Ramirez [11] reported that the use of a higher stress range resulted in lower splitting load. Investigation of current test results shows that all but one of the three cases considered support the finding. The average splitting load for U7361 and U7362

with a stress range of 8.74 ksi was 8.85 kips, and 8.5 kips for U7363 with a stress range of 15 ksi. The average splitting load of U11241 and U11242 with a stress range of 8.74 ksi was 25.5 k, while the splitting load for U11243 with a stress range of 15 ksi was 20 kips. However, the average splitting load for U11301 and U11302 with a stress range of 8.74 ksi was 24.5 kips, and 27.29 kips for U11303 with a stress range of 15 ksi.

Another way to compare the difference in splitting load and failure load is by looking at the mean stress. Table 4.75 shows the evaluation of effect of mean stress. It is seen that except for U7301 and the average of U11301 and U11032, all other results show that splitting load increases with the increase in mean stress for uncoated specimens. An increase in mean stress also increased the failure load for uncoated specimens. Results of repeated loading tests for all the specimens consistently show an increase in failure load as the mean stress increases. However, using the mean stress criteria, the opposite results are true for Cleary's tests [11]. The mean stress for 15 ksi stress range in Cleary's test was 32.5 ksi and 30 ksi for a stress range of 10 ksi, hence the increase in mean stress caused a decrease in splitting load. For failure load, of the three cases considered in Cleary's study, two cases show an increase in failure load as the mean stress increases, one case indicated that an increase in the mean stress resulted in the decrease in failure load. For epoxy-coated specimens, results for splitting load and failure load were scattered in both the current tests and Cleary's tests so no conclusion can be drawn.

Repeated loading has the effect of reducing the difference in crack width between uncoated specimens and epoxy-coated specimens. This finding is consistent with the Cleary and Ramirez study. Individual crack widths for Type A specimens were found to

be approximately 23% wider in specimens with epoxy-coated steel in the early cycles of loading. After 1 million cycles the difference was reduced to 6.3%. For Type B specimens, the crack width of epoxy-coated specimens was approximately 30% larger and reduced to 19% after application of 1 million cycles of repeated loading. In Cleary's tests, the difference initially was about 20% and reduced to 12% after 1 million cycles of repeated loading. As discussed by Cleary and Ramirez [11], this phenomenon can be explained from the mechanics point of view. According to Lutz [22], for bars with rib face angles larger than about 40 degrees, the slip is due almost entirely to the crushing of the concrete in front of the ribs. For uncoated specimens, the friction component along the rib surface reduces the direct bearing force resulted in smaller crushing action. The repeated loading reduced the friction component as the interface between the rib and concrete is smoothed and the surface irregularities diminished. Since the friction component is reduced, the amount of crushing action will increase, the cracks become wider, so the differences between the coated and uncoated members are reduced.

Results of the tests also indicate that fewer but wider cracks occur in members with epoxy-coated steel. Although members with epoxy-coated steel have fewer flexural cracks, the total crack width is greater or nearly the same as that of members with uncoated bars, even after 1 million cycles of repeating loading, therefore the risk of corrosion due to penetration of harsh material such as deicing could also be higher or the same as members with uncoated steel.

4.3.10 Summary

Results from observation and analysis of the cracking data are summarized as the following:

1. The crack patterns of uncoated specimens are essentially the same as for coated specimens. However, fewer but wider flexural cracks were found in members with epoxy-coated steel. The total crack width of epoxy-coated specimens is greater than that of uncoated specimens, but the difference is reduced by repeated loading.
2. The flexural cracking load for members with epoxy-coated reinforcement was lower than that of members with uncoated bars. However, the difference in the first flexural cracking load was not significant. The splitting cracking load was also lower for epoxy-coated specimens. The average E/U ratios of cracking loads for Type A specimens was 0.924, and 0.941 for Type B specimens.
3. The combination of c/d_b and l_s/d_b ratio is a dominant factor that influences the splitting load. Hypothetically there would be an optimum combination of these ratios that gives the optimum splitting load.
4. For uncoated specimens, test results consistently showed that an increase in mean stress resulted in an increase in the failure load. Also, approximately 80% of the repeated loading tests showed that a higher mean stress gave a higher splitting load for uncoated specimens. Nevertheless, the findings on the effect of mean stress on splitting load disagree with those of the previous study by Cleary and Ramirez [11]. Future works are expected to clarify this matter.

5. The uncoated specimens are more ductile than the epoxy coated specimen because the post-splitting load for uncoated specimens is larger than that of epoxy-coated specimens.
6. Stress range influences the splitting load. In all but one of the three cases considered, a higher stress range resulted in a lower splitting load. This is in agreement with previous work by Cleary and Ramirez [11].
7. Results of tests on the diamond deformation pattern provide an indication that members with a diamond deformation pattern might have larger crack widths compared to members with a spiral deformation pattern. Also, the extra thickness of coating seems to affect smaller diameter bars more. Additional data are needed for verification.

4.4 Bond Strength

In this section, the bond strength of members with epoxy-coated steel and members with uncoated steel subjected to repeated loading is investigated. The effects of concrete compressive strength, stress range, repeated loading, coating thickness, and deformation pattern on bond ratio are each evaluated. Evaluations are also made on the current ACI 318-89 development length provisions. Based on the finding of this study and a previous study by Cleary and Ramirez, changes to the ACI 318-89 provisions for anchorage of epoxy-coated bars are proposed.

4.4.1 Definition

The average bond stress developed by an anchored bar is defined as the force developed in the bar divided by the surface area of the bar.

$$u = \frac{f_y A_b}{\pi d_b l_s} \quad (4.1)$$

Where,

u = bond stress (psi)

f_y = bar yielding stress (psi)

A_b = area of bar (in.²)

d_b = bar diameter (in.)

l_s = splice length (in.)

substituting the failure stress f_s for f_y , and simplifying gives,

$$u = \frac{f_s d_b}{4 l_s} \quad (4.2)$$

The bond ratio is defined as the ratio of average bond stress developed in the splice at failure for a specimen containing epoxy-coated steel to its companion specimen containing uncoated steel. Using equation (4.2) for uncoated and epoxy-coated bars, and simplifying yields,

$$\text{Bond Ratio} = \frac{f_s(\text{epoxy-coated})}{f_s(\text{uncoated})} \quad (4.3)$$

So, the bond ratio can be taken as the ratio of the failure stress developed in the epoxy-coated steel splice to that of uncoated steel. The failure stress was calculated

assuming a Hognestadt stress distribution in the concrete compression zone and no contribution from the concrete in the tension zone. The bond efficiency is defined as the measured bond stress relative to that obtained using either Orangun predicting equation [14] or ACI 318-89 Building Code requirements [9].

4.4.2 Bond Ratio

Column 7 of Tables 4.77 and 4.78 contains the bond ratio for Type A and Type B specimens respectively. For Type A specimens, the bond ratio measured in these tests ranged from 0.643 to 0.952 with an average value of 0.78 for specimens tested with repeated loading, and 1.00 for specimens tested with single cycle loading. For Type B specimens, the values ranged from 0.583 to 0.856 with an average value of 0.750 for specimens tested with repeated loading, and 0.78 for static loading test.

4.4.2.1 Effect of Concrete Compressive Strength

Table 4.79 presents the evaluation of the influence of concrete compressive strength on bond ratio. The trend of test results of Type A and Type B specimens subjected to repeated loading indicates a reduction in bond ratio with increasing concrete compressive strength. For Type A specimens, the average bond ratio for the beams with concrete compressive strength of 3000 psi was 0.882. For the 3900-4000 psi concrete compressive strength the ratio was 0.841 for the repeated loading tests, and 1.00 for the static loading tests. For the 4700 psi the ratio was 0.824. For the 5200-5300 psi test, the ratio was 0.679. For Type B specimens, the average bond ratio for the specimens with

concrete compressive strength of 3000 psi was 0.835. For the 3900-4000 psi concrete compressive strength, the ratio was 0.583 for repeated loading test and 0.784 for static loading test. For the 4700 psi test the ratio was 0.791 For the 5200-5300 psi test the ratio was 0.760.

The influence of concrete strength found in the current study is consistent with results from previous studies. In 1989, based on results of tests of eight slab specimens plus additional results from tests of Johnston and Zia [2] and those of Treece and Jirsa [21], Cleary and Ramirez [4] found a reduction in bond strength with increasing concrete strength. Similar trend was also reported by Hamad et al [19] in 1990. From tests of 96 half beam specimens, Grundhoffer et al. [26] found that for No.6 bars, the amount of reduction in bond strength due to epoxy-coating was unaffected by concrete strength, whereas for the No.11 bars the amount of reduction in bond strength due to epoxy-coating increased as the concrete strength increased.

4.4.2.2 Effect of Stress Range

Table 4.80 contains the evaluation of the effect of stress range on bond ratio. It is seen that there was no clear influence of the stress range used in the repeated loading tests. For Type A specimens, the average bond ratio of specimens tested with an 8.74 ksi stress range was 0.771, and 0.841 for a stress range of 15 ksi. For Type B specimens, the average bond ratio of specimens tested with 8.74 ksi stress range was 0.761, and 0.699 for a stress range of 15 ksi.

Cleary and Ramirez [11] found that the stress range used during cycling did not

affect the bond ratio. For the beam tested with a 10 ksi stress range, the average bond ratio was 0.87. For the 15 ksi stress range tests, the average bond ratio was 0.86.

4.4.2.3 Effect of Repeated Loading

Cleary and Ramirez [11] found an increase in bond ratio due to the application of repeated loads. It was stated that overall, repeated loading appears to increase the bond ratio by increasing the failure load of beams with epoxy-coated reinforcement more than for uncoated reinforcement. A slight increase in bond ratio due to application of repeated loads was also reported by Johnston [2].

Based on the very limited amount of data for static tests available in the current study for both types of specimens, the bond ratios for static loading were higher than the average bond ratio of specimens subjected to repeated loading.

4.4.2.4 Effect of Extra-Thickness of Coating and Deformation Pattern

Treece and Jirsa [21] found that the reduction in bond strength is insensitive to variations in the coating thickness when the average coating thickness is greater than 5 mils and less than 14 mils. Comparison of series 7361, 7362, 736SX, 11301, 11302, and 1130SX indicates that the effect of extra-thickness of coating (> 15 mils) on bond ratio is not significant. Comparing series 11301, 11302, 1130SX, and 1130DX, the only specimen series with diamond deformation pattern (series 1130DX) has the lowest bond ratio. The bond ratio for series 11301, 11302, and 1130SX was 0.75, 0.76, and 0.77 respectively, whereas the bond ratio for series 1130DX was 0.64, about 14 % lower than

others.

Using relative bearing area (ratio of the bearing area of the ribs to the shearing area between ribs) as predictor of the bond strength of deformed bars, Choi [23] found that E/U decreases as the rib bearing area or the bearing area ratio decreases. The same trend was observed by using an alternative parameter, bearing area ratio (ratio of the rib bearing area per inch length to the nominal cross sectional area of the bar). The current study has only one series of specimens with diamond deformation pattern bars, series 1130DX, which has the lowest relative rib bearing area as well as lowest rib bearing area ratio. The bond ratio was 0.64, the lowest for Type B specimens if series 11303 which failed in fatigue is excluded.

4.4.3 Bond Stress With Orangun Predicting Equation

The equation developed by Orangun [14] to predict the average bond stress accounts for concrete cover, bar size, anchorage length, concrete strength, and the confinement by transverse steel. The equation can be modified for predicting the failure stress. Substituting equation (4.1) into the Orangun equation,

$$u = (1.2 + 3 \frac{C}{d_b} + 50 \frac{d_b}{l_s} + K_{tr}) \sqrt{f'_c} \quad (4.4)$$

and solving for f_s yields,

$$f_s = 4 \frac{l_s}{d_b} (1.2 + 3 \frac{C}{d_b} + 50 \frac{d_b}{l_s} + K_{tr}) \sqrt{f'_c} \quad (4.5)$$

Where

$$K_{tr} = \frac{a_{tr}f_{yt}}{500sd_b} \leq 3.0, \text{ and } \frac{C}{d_b} \leq 2.5 \quad (4.6)$$

a_{tr} = area of transverse steel (in.²)

C = the smaller of C_b or C_s (in.)

C_b = clear bottom cover to main reinforcement (in.)

C_s = half clear spacing between bars splices or half available concrete width per bar splice resisting splitting in the failure plane (in.)

d_b = bar diameter (in.)

f_{yt} = yield strength of transverse reinforcement (psi)

K_{tr} = an index of the transverse steel provided along the anchored bar

l_s = splice length (in.)

The bond stresses and the corresponding bond efficiency calculated using Orangun equation are listed in columns 8 and 13 of Tables 4.77 and 4.78. The results indicate that the Orangun equation is reliable in predicting the bond stress for uncoated specimens. For Type A specimens subjected to repeated loading, the average bond efficiency with respect to Orangun's equation was 0.94 with a standard deviation of 0.09 for specimens with uncoated steel, For Type B specimens subjected to repeated loading, the average bond efficiency with respect to Orangun's equation was 0.91 with a standard deviation of 0.05 for specimens with uncoated steel. The Orangun equation, originally developed from test data on uncoated steel, resulted in lower calculated bond stress for epoxy-coated bars. For Type A specimens, the mean bond efficiency for epoxy coated specimens was 0.74 with a standard deviation of 0.12. For Type B specimens, the bond efficiency was 0.68 with

a standard deviation of 0.09 for epoxy-coated specimens. The single cycle loading test also gave lower predicted bond stress. For the Type A static loading test, the bond efficiency was 0.82 for specimens containing either uncoated steel or epoxy-coated bars. For Type B static loading test, the bond efficiency was 0.86 for specimens containing uncoated steel, and 0.68 for specimens containing epoxy-coated bars.

Similar results were reported by Cleary and Ramirez [11]. For the beams with uncoated steel subjected to repeated loading, the average mean bond efficiency was 0.981. The value for specimens with epoxy coated bars subjected to repeated loading was 0.860. For the single cycle loading test, the mean bond efficiency was found to be 0.718. These results are shown in Table 4.81.

4.4.4 Bond Stress With ACI 318-89 Provisions

The basic development length factor according to section 12.2.2. ACI 318-89 Building Code is given by :

$$l_{db} = \frac{0.04 A_b f_y}{\sqrt{f'_c}} * (\text{modification factor}) \quad (4.7)$$

Substituting l_s for l_{db} , f_s for f_y , and solving for f_s yields,

$$f_s = \frac{l_s \sqrt{f'_c}}{0.04 A_b (\text{modification factor})} \quad (4.8)$$

For both types of specimens, the applicable modification factors are 1.3 for a class B splice according to section 12.15, and 1.5 for epoxy-coating according to section

12.2.3.4 of the ACI 318-89 Building Code. The modification factor for bar spacing, cover, and transverse reinforcement from section 12.2.3.4 is 0.8 for Type A specimens. This factor is 1.0 for Type B specimens according to section 12.2.3.1 of the ACI 318-89 code [9]. Four cases are to be considered to evaluate the modification factors as required by ACI 318-89 provisions. The first case is the bond without splice and epoxy coating modification factors, the second case is the bond with the application of splice factor only, the third case is the bond without splice factor but with epoxy coating factor, and the fourth case is the bond with both splice and epoxy coating factor. The first and second cases are intended for uncoated bars, while the third and fourth cases are intended for epoxy-coated bars. Referring to Tables 4.77 and 4.78, the bond stresses for each case are listed in columns 9 through 12, whereas the corresponding bond efficiencies are listed in columns 14 through 17. Table 4.82 gives a summary of the bond efficiency results. The test results for each of the cases are presented in the following section.

4.4.4.1 Case 1: No Splice and No Epoxy Coating Factors

For Type A specimens, the mean bond efficiency with repeated loading tests was found to be 1.23 with a standard deviation of 0.12 for uncoated bars, for epoxy-coated bars the value was 0.96 with a standard deviation of 0.16. For the single cycle test, the bond efficiency was 1.07 for either coated or uncoated specimens. For Type B specimens, the mean bond efficiency with repeated loading tests was found to be 1.70 with a standard deviation of 0.10 for uncoated bars, for epoxy-coated bars the value was 1.27 with a standard deviation of 0.18. For the single cycle test, the bond efficiency was 1.62 for

uncoated bars, and 1.27 for epoxy coated bars.

4.4.4.2 Case 2 : Splice Factor Only

For Type A specimens, the mean bond efficiency was found to be 1.60 with a standard deviation of 0.16 for uncoated bars, for epoxy-coated bars the value was 1.25 with a standard deviation of 0.21. For the single cycle test, the bond efficiency was 1.40 for either coated or uncoated specimens. For Type B specimens, the mean bond efficiency for repeated loading tests was found to be 2.21 with a standard deviation of 0.13 for uncoated bars, for epoxy-coated bars the value was 1.65 with a standard deviation of 0.23. For the single cycle test, the bond efficiency was 2.10 for uncoated bars, and 1.65 for epoxy coated bars.

4.4.4.3 Case 3 : Epoxy Coating Factor Only

The factor of 1.5 for epoxy-coated bars has been applied for either Type A or Type B specimens for the beams containing epoxy-coated bars but the splice factor has not been applied. For Type A specimens, the mean bond efficiency for repeated loading tests was found to be 1.44 with a standard deviation of 0.24 for epoxy-coated bars. For the single cycle test, the bond efficiency was 1.61 for coated specimens. For Type B specimens; the mean bond efficiency for repeated loading tests was found to be 1.90 with a standard deviation of 0.26 for epoxy-coated bars. For the single cycle test, the bond efficiency was 1.90 for epoxy-coated bars.

4.4.4.4. Case 4: Splice and Epoxy Coating Factors

For Type A specimens, the average bond efficiency for specimens with epoxy-coated bars with the epoxy and splice modification factors was found to be 1.87 with a standard deviation of 0.31 for repeated loading tests. For the single cycle test, the bond efficiency was 2.09 for coated specimens. For Type B specimens, the mean bond efficiency for epoxy-coated specimens was found to be 2.47 with a standard deviation of 0.34 for repeated loading tests, and 2.47 for the single cycle loading test.

4.4.5 Evaluation of ACI 318-89 Development Length Provisions

Previous studies [2-7,11,21] have indicated that epoxy coating reduces the bond strength of members reinforced with epoxy-coated bars. The bond ratio in these studies ranged from 0.67 to 0.95. Test results in this study also indicate that epoxy coating reduces the bond strength. The average bond ratio was found to be 0.78 for Type A specimens and 0.75 for Type B specimens. These specimens had a minimum cover of 2.5 inches. This resulted in a cover to bar diameter ratio of 2.86 for Type A specimens, and 1.77 for Type B specimens. If the lesser value is used, an epoxy-coated bar development length modification factor of $1/0.75 = 1.33$ is found. This is less than the current ACI 318-89 epoxy-coated bar development length modification factor of 1.5 for cover to bar diameter ratio less than 3. This requirement was based on the relatively limited test data of Treece and Jirsa study [3].

In a comprehensive study of data available in the literature, Hester et al. [6,24] suggested that a epoxy-coated bar factor of 1.5 is too high for bars with as little as two

bar diameters of cover, and factors of 1.15 and 1.2 are too low for bars with a minimum of three bar diameters of cover. It was further suggested that a bond ratio of 0.74 conservatively represents the effect of epoxy coating on splice strength. This value is very close to the bond ratio of 0.75 and 0.78 found in the current study. Hester et al further recommended that the inverse of 0.74, 1.35, can be used as an epoxy-coated bar development length modification factor whether the anchored bar is confined with transverse reinforcement or not. It was further pointed out that since the provisions of ACI 318-89 [9] and the Orangun equation [14] account for improvements in bond strength provided by transverse reinforcement, a single development length modification factor is satisfactory in all cases. It was also recommended that a maximum factor of 1.35 is also applicable for use in the AASHTO Bridge Specifications for bars with transverse reinforcement providing values of K_{tr} 3.0 and a factor of 1.20 if the values of K_{tr} 3.0. A reduced development length factor could be used in conjunction with the AASHTO Bridge Specifications [10] because these specifications do not take advantage of improvements in bond strength provided by transverse reinforcement. Hester et al. also suggested that the degree of transverse reinforcement does not affect the percentage decrease in splice strength caused by epoxy-coatings. In addition, transverse reinforcement improves the strength of splices containing both coated and uncoated bar reinforcement. The percentage increase in strength is approximately the same for both coated and uncoated bars for equal amounts of transverse reinforcement. This is different from the findings of Hamad and Jirsa [12, 19] where the improvement in bond strength for epoxy-coated bar splices is found to be greater than uncoated bar splices.

The Hamad and Jirsa [12,19] study consisted of tests on 12 specimens (3 series) in negative bending with multiple splices in a constant moment region at the center of the beam. The variables used were bar size (# 6 and # 11), bar spacing, and amount of transverse reinforcement in the splice region. The results indicated that transverse steel improve the bond capacity. The improvement is greater for epoxy coated bar splices than uncoated bar splices. The improvement is independent of the number of splices, bar size, or bar spacing. Furthermore, using results of the study and results of other tests on epoxy-coated bars [3, 23, 25], Hamad and Jirsa [12] proposed the following design recommendations:

1. ACI upper limit of 100 psi set on the value $\sqrt{f'_c}$ of section 12.1.2 could be raised to a value of 120 to 130 psi.
2. section 12.2.3.1(b) could be changed from "minimum cover not less than specified in 7.7.1" to "a minimum cover not less than d_b where d_b is the diameter of the bar being developed."
3. section 12.2.3.2 changed to "For bars with cover of d_b or less and with clear spacing $2 d_b$ or less, and without transverse reinforcement along the development length.
4. Section 12.2.4.3 can be changed to read as follows:
 - (a) Bars with cover less than $3 d_b$ or clear spacing between bars less than $6 d_b$1.5
 - (b) Bars with cover larger than $3 d_b$ and clear spacing between

- bars larger than $6 d_b$ 1.2
- (c) Bars with transverse reinforcement $A_{tr} > d_b sN/(120)$ along
the development length, regardless of the amount of cover
or clear spacing between bars1.2

5. For epoxy-coated top reinforcement, the larger of the factors for top reinforcement of 12.2.4.1 and the applicable factor for epoxy-coated reinforcement of 12.2.4.3 shall be used.

6. Add a new section 12.2.4.4 :

12.2.4.4 - The basic development length l_{db} modified by factors from sections 12.2.3.1, 12.2.3.2, 12.2.3.3, 12.2.4.1, or 12.2.4.3 need not exceed $2.0 l_{db}$.

add a new paragraph to Section 12.15.1:

The splice length modified by the factors in Section 12.15.1 need not exceed $2.0 l_{db}$.

Table 4.82 summarizes the bond efficiency of current study and Cleary and Ramirez study [11]. It is observed that the Orangun bond prediction equation gives good results for uncoated specimens subjected to repeated loading. For epoxy-coated specimens the Orangun equation results in a lower failure stress. Observation of the bond efficiency relative to the ACI 318-89 provisions revealed that the current ACI Code conservatively predicted the failure stress. The bond efficiencies based on ACI provisions without the application of splice and epoxy factors were greater than 1.0, except for Type A epoxy-coated specimens in which the bond efficiency was 0.96. Cleary found the bond efficiency without the splice and epoxy factors did not adequately ensure safety. The bond efficiency

from Cleary's study was 1.053 for uncoated specimens with repeated loading, and 0.940 for epoxy coated specimens with repeated loading.

The application of splice modification factor or epoxy coating modification factor alone provides adequate conservatism in bond efficiencies for all tests from the current study. Overall, the average bond efficiencies ranged from 1.25 to 2.21 with individual bond efficiency mostly greater than 1.5. For Cleary's tests, the average bond efficiencies with the splice factor or the epoxy coating factor only ranged from 1.107 to 1.369 for repeated loading tests. For static loading tests, the bond efficiency for Cleary's tests with a splice factor alone and tested monotonically was 1.012 with a standard deviation of 0.097. The bond efficiency for epoxy-coated specimens with the epoxy coating factor alone for Cleary's tests was 0.935 with a standard deviation of 0.090, which was slightly unconservative. Notice that the applicable epoxy coating modification factor for the current study was 1.5, whereas for Cleary's tests, the applicable epoxy coating factor was 1.2. The splice factor was 1.5 for either the current study or Cleary's study.

As discussed in the previous section, results of the current and Cleary studies indicate that the failure stresses computed according to equation (4.8) with the application of either the splice factor or epoxy coating factor alone is adequate, with the only exception being the static tests of epoxy-coated specimens in Cleary's study. This indicates that the effects of the splice modification factor and epoxy coating modification are not necessarily cumulative. Previous study by Hamad and Jirsa [12] also suggested that "factors for splices, top casting, epoxy coating, cover, spacing, and transverse reinforcement are not all cumulative". It was pointed out that "worst" case conditions are

not likely to occur simultaneously for all critical parameter. In cases that all these factors are applicable, it was recommended that an upper factor of 2.0 be set on the product of modification factors for all cases of uncoated and epoxy-coated reinforcing bars.

From the analysis of the results of current study and reviews of the studies by Hester et al. and Hamad and Jirsa , several points can be made:

1. The ACI 318-89 provisions on splices are over-conservative.
2. The modification factors account for the effect of splice, epoxy coating, and casting position are not necessarily cumulative.
3. The application of a single modification factor for epoxy coating as suggested by Hester et. al. is justified by the results of current and Cleary and Ramirez [11] studies.
4. Hester et al. suggestion of a 1.35 epoxy coating modification factor is in agreement with the epoxy coating factor of 1.33 found in this study.

4.4.6 Recommendation

Based on the results from this study, the following suggestions and design recommendations on ACI 318-89 are proposed :

1. A single epoxy coating modification factor of 1.35 can be used to account for the effect of epoxy coating on the splice strength for cover to bar diameter ratio greater than 1.8.
2. In the case that both the splice modification factor and epoxy coating modification factor are applicable, only the larger of the modification factors needs to be

employed. In this case, the 1.35 epoxy coating modification factor will govern.

Thus, the ACI section 12.2.4.3 on epoxy coated reinforcement may be simplified to read as follow :

12.2.4.3 - Epoxy-coated reinforcement

- (a) Bars with cover greater than $1.8 d_b$1.35
- (b) The modification factors from section 12.2.4.1, 12.2.4.2 and 15.1. need not be applied

Add a new section 12.2.4.4:

12.2.4.4 - For uncoated bars, the larger of the factors for top reinforcement of 12.2.4.1 and the applicable factor of 12. 15. shall be used.

Using the proposed modification factor, the bond efficiency ratios of the current and Cleary and Ramirez studies were calculated. The results are presented in Tables 4.83 and 4.84. According to the proposed modification factor, the applicable modification factor for either the current study or Cleary the and Ramirez study is 1.3 for uncoated specimens, and 1.35 for epoxy coated specimens. A comparison of the bond efficiency according to current ACI 318-89 provisions with the proposed epoxy coating modification factor is presented in Table 4.85. It can be seen that the bond efficiency of uncoated specimens for the cases considered remains unchanged. However, the values of average bond efficiency for epoxy coated bar, while still give conservative result, have been dropped by 31% for the current study, and 13 % for the Cleary and Ramirez [11] study. This indicates that the proposed modification factor is satisfactory. It also has the advantages of being simple, easy to implement, more economical, and yet still provides

adequate conservatism.

4.4.7 Conclusions

From the analysis of bond strength from the current study, the following conclusions can be made:

1. Concrete compressive strength affects the bond ratio. A higher concrete compressive strength gives a lower bond ratio.
2. The effect of stress range on bond ratio is still unclear. Previous study by Cleary and Ramirez [11] found no influence of the stress range on bond ratio.
3. From the very limited data on static loading tests, no conclusion can be made for the effect of repeated loading on bond ratio. However, an increase in bond ratio due to repeated loading was reported in a previous study by Cleary and Ramirez [11].
4. The influence of extra-thickness of coating on bond ratio is not significant. The test result of diamond deformation patterns indicates that bond ratio decreases as relative rib area or bearing area ratio decreases.
5. The Orangun equation [14] gives good results in predicting the bond stress for uncoated bars. However, it predicts a lower failure stress for epoxy-coated bars.
6. The ACI 318-89 provisions on splices are overconservative.
7. The splice modification factor and epoxy coating modification factor are not necessarily cumulative.
8. The application of a single modification factor for epoxy coating as suggested by

Hester et. al is justified by the results of this and Cleary and Ramirez [11] studies.

9. Hester et al. suggestion of a 1.35 epoxy coating modification factor is in agreement with the epoxy coating factor of 1.33 found in this study.
10. The proposed design recommendation gives satisfactory results.

4.5 Summary

The experimental results from the laboratory phase were described and analyzed in this chapter. The structural performance of slab specimens reinforced with epoxy-coated bars under repeated loading of the type typically encountered in bridges was compared with that of companion specimens reinforced with uncoated bars. The structural evaluation included aspects of deflections, cracking, and bond strength. In the next chapter, the details and results of a condition survey of a representative sample of bridges in Indiana are discussed.

**Table 4.1 End and Total Deflections
Type A Specimens, $P = 2k$**

Specimen	Ave. End Defl. (inches)				Ave. Total Defl. (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
U7241	0.443	0.497	0.574	0.600	0.483	0.545	0.630	0.660
E7241	0.476	0.513	0.557	0.588	0.520	0.561	0.613	0.648
U7242	0.428	0.462	0.486	0.501	0.469	0.506	0.529	0.545
E7242	0.401	0.431	0.466	0.488	0.436	0.469	0.507	0.531
U7301	0.540	0.600	0.652	0.691	0.592	0.659	0.717	0.761
E7301	0.623	0.689	0.738	0.794	0.684	0.760	0.817	0.881
U7361	0.482	0.537	0.571	0.604	0.530	0.590	0.629	0.666
E7361	0.564	0.621	0.656	0.699	0.616	0.681	0.721	0.769
U7362	0.483	0.530	0.573	0.594	0.535	0.588	0.636	0.660
E7362	0.499	0.589	0.662	-	0.552	0.654	0.742	-
U7363	0.514	0.591	0.639	0.686	0.565	0.649	0.703	0.755
E7363	0.515	0.577	0.620	0.658	0.563	0.632	0.681	0.725
U736SX	0.534	0.621	0.682	0.707	0.595	0.673	0.732	0.756
E736SX	0.566	0.624	0.694	-	0.630	0.698	0.782	-
Ave Unc	0.489	0.548	0.597	0.626	0.538	0.602	0.654	0.686
Stdev Unc	0.043	0.058	0.066	0.073	0.049	0.062	0.070	0.078
Ave Epo	0.520	0.578	0.627	0.645	0.572	0.636	0.695	0.711
Stdev Epo	0.072	0.084	0.091	0.115	0.081	0.096	0.106	0.131
E/U	1.064	1.053	1.051	1.031	1.062	1.058	1.063	1.036

Table 4.2 E/U Ratios of End and Total Deflections
Type A Specimens, P = 2 k

Specimen Series	Ave. End Defl. (inches)			Ave. Total Defl. (inches)				
	Cycle Number			Cycle Number				
	2	100000	450000	1000000	2	100000	450000	1000000
7241	1.076	1.031	0.970	0.980	1.077	1.031	0.973	0.982
7242	0.936	0.934	0.958	0.974	0.929	0.925	0.958	0.975
7301	1.155	1.147	1.131	1.149	1.157	1.153	1.139	1.158
7361	1.169	1.156	1.148	1.157	1.162	1.153	1.145	1.154
7362	1.033	1.110	1.155	-	1.031	1.112	1.166	-
7363	1.001	0.976	0.970	0.960	0.997	0.974	0.969	0.961
736SX	1.060	1.005	1.018	-	1.059	1.037	1.069	-
Average	1.061	1.051	1.050	1.044	1.059	1.055	1.060	1.046
Std. Dev	0.082	0.087	0.091	0.100	0.084	0.088	0.092	0.101

Table 4.3 End and Total Deflections
Type A Specimens, $P = 3.5 \text{ k}$

Specimen	Ave. End Defl. (inches)				Ave. Total Defl. (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
U7241	0.625	0.682	0.757	0.782	0.685	0.750	0.834	0.863
E7241	0.661	0.701	0.742	0.770	0.725	0.771	0.819	0.851
U7242	0.579	0.607	0.635	0.651	0.638	0.669	0.695	0.714
E7242	0.547	0.571	0.599	0.616	0.598	0.623	0.655	0.674
U7301	0.721	0.778	0.836	0.877	0.793	0.857	0.923	0.970
E7301	0.822	0.887	0.941	1.005	0.905	0.982	1.045	1.118
U7361	0.652	0.711	0.750	0.788	0.721	0.786	0.830	0.874
E7361	0.744	0.805	0.845	0.889	0.817	0.887	0.933	0.982
U7362	0.637	0.696	0.742	0.764	0.708	0.775	0.827	0.852
E7362	0.671	0.768	0.848	-	0.744	0.856	0.952	-
U7363	0.690	0.774	0.824	0.875	0.761	0.853	0.910	0.965
E7363	0.686	0.755	0.799	0.840	0.754	0.831	0.881	0.929
U736SX	0.732	0.807	0.891	0.920	0.816	0.902	0.966	0.995
E736SX	0.755	0.817	0.896	-	0.841	0.915	1.010	-
Ave Unc	0.662	0.722	0.776	0.808	0.732	0.799	0.855	0.890
Sdev Unc	0.055	0.069	0.083	0.091	0.062	0.079	0.089	0.097
Ave Epo	0.698	0.758	0.810	0.824	0.769	0.838	0.899	0.911
Sdev Epo	0.087	0.101	0.113	0.144	0.098	0.116	0.132	0.164
E/U	1.054	1.049	1.043	1.019	1.051	1.049	1.052	1.023

Table 4.4 E/U Ratios of End and Total Deflections
Type A Specimens, $P = 3.5$ k

Specimen Series	Ave. End Defl. (inches)			Ave. Total Defl. (inches)		
	Cycle Number			Cycle Number		
	2	100000	450000	2	100000	450000
7241	1.058	1.028	0.980	1.058	1.028	0.983
7242	0.945	0.940	0.943	0.937	0.932	0.942
7301	1.140	1.141	1.125	1.142	1.146	1.132
7361	1.141	1.132	1.128	1.133	1.129	1.124
7362	1.054	1.104	1.144	1.051	1.104	1.151
7363	0.994	0.975	0.969	0.990	0.974	0.969
736SX	1.032	1.012	1.006	1.031	1.014	1.046
Average	1.052	1.048	1.042	1.049	1.047	1.050
Ste. Dev	0.072	0.079	0.087	0.073	0.081	0.087
						0.097

Table 4.5 End and Total Deflections
Type A Specimens, P = Peak Repeating Load

Specimen	Ave. End Defl. (inches)				Ave. Total Defl. (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
U7241	0.625	0.682	0.757	0.782	0.685	0.750	0.834	0.863
E7241	0.661	0.701	0.742	0.770	0.725	0.771	0.819	0.851
U7242	0.579	0.607	0.635	0.651	0.638	0.669	0.695	0.714
E7242	0.547	0.571	0.599	0.616	0.598	0.623	0.655	0.674
U7301	0.853	0.890	0.944	0.983	0.941	0.983	1.044	1.088
E7301	0.964	1.015	1.056	1.138	1.066	1.126	1.174	1.269
U7361	0.896	0.934	0.973	1.011	0.996	1.038	1.083	1.127
E7361	1.003	1.044	1.087	1.122	1.107	1.157	1.205	1.246
U7362	0.869	0.904	0.945	0.978	0.970	1.010	1.058	1.095
E7362	0.954	1.004	1.077	-	1.064	1.122	1.212	-
U7363	0.940	1.002	1.057	1.104	1.040	1.109	1.171	1.222
E7363	0.907	0.974	1.016	1.046	1.003	1.079	1.128	1.165
U736SX	1.017	1.077	1.152	1.187	1.137	1.201	1.257	1.294
E736SX	1.041	1.081	1.167	-	1.164	1.213	1.318	-
Ave Unc	0.825	0.871	0.923	0.957	0.915	0.966	1.020	1.058
Stdev Unc	0.162	0.169	0.175	0.184	0.185	0.191	0.194	0.203
Ave Epo	0.868	0.913	0.963	0.938	0.961	1.013	1.073	1.041
Stdev Epo	0.188	0.196	0.209	0.233	0.214	0.224	0.241	0.265
E/U	1.052	1.048	1.043	0.981	1.050	1.049	1.052	0.984

Table 4.6 E/U Ratios of End and Total Deflections
Type A Specimens, P = Peak Repeating Load

Specimen Series	Ave. End Defl. (inches)			Ave. Total Defl. (inches)		
	Cycle Number			Cycle Number		
	2	100000	450000	2	100000	450000
7241	1.058	1.028	0.980	1.058	1.028	0.983
7242	0.945	0.940	0.943	0.937	0.932	0.942
7301	1.131	1.141	1.119	1.133	1.146	1.125
7361	1.119	1.118	1.117	1.112	1.114	1.113
7362	1.098	1.110	1.139	1.096	1.110	1.146
7363	0.965	0.972	0.962	0.964	0.973	0.963
736SX	1.024	1.003	1.013	1.024	1.010	1.048
Average	1.048	1.045	1.039	1.046	1.045	1.046
Std. Dev	0.074	0.079	0.083	0.075	0.080	0.084
						0.099

Table 4.7 End and Total Deflections
Type B Specimens, P = 6 k

Specimen	Ave. End Defl. (inches)			Ave. Total Defl. (inches)		
	Cycle Number			Cycle Number		
	2	10000	450000	2	10000	450000
U11241	0.213	0.251	0.279	0.293	0.212	0.250
E11241	0.236	0.259	0.291	0.294	0.239	0.263
U11242	0.218	0.241	0.291	0.272	0.216	0.243
E11242	0.222	0.237	0.249	0.272	0.229	0.246
U11243	0.226	0.262	0.291	0.316	0.240	0.286
E11243	0.242	0.276	0.302	0.308	0.246	0.284
U11301	0.242	0.267	0.287	0.291	0.252	0.278
E11301	0.236	0.260	0.283	0.287	0.243	0.268
U11302	0.214	0.245	0.267	0.287	0.225	0.256
E11302	0.233	0.263	0.292	0.339	0.241	0.274
U11303	0.203	0.258	0.313	0.326	0.211	0.269
E11303	0.219	0.276	-	-	0.222	0.281
U1130SX	0.224	0.248	0.282	0.291	0.242	0.269
E1130SX	0.220	0.245	0.275	0.283	0.225	0.250
U1130DX	0.237	0.275	0.304	0.348	0.248	0.287
E1130DX	0.282	-	-	-	0.307	-
Ave Unc	0.222	0.256	0.289	0.303	0.231	0.267
Stdev Unc	0.013	0.012	0.014	0.025	0.017	0.016
Ave Epo	0.236	0.259	0.282	0.297	0.244	0.267
Stdev Epo	0.020	0.015	0.019	0.024	0.027	0.015
E/U	1.062	1.014	0.975	0.980	1.058	0.998
						0.971
						0.976

Table 4.8 E/U Ratios of End and Total Deflections
Type B Specimens, P = 6 k

Specimen Series	Ave. End Defl. (inches)				Ave. Total Defl. (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
11241	1.106	1.033	1.042	1.005	1.129	1.051	1.062	1.013
11242	1.015	0.981	0.854	1.001	1.063	1.015	0.891	1.060
11243	1.073	1.054	1.039	0.973	1.025	0.993	1.040	0.977
11301	0.972	0.973	0.985	0.984	0.965	0.963	0.978	0.976
11302	1.086	1.074	1.094	1.179	1.070	1.070	1.088	1.181
11303	1.079	1.070	-	-	1.052	1.047	-	-
1130SX	0.979	0.988	0.975	0.973	0.928	0.932	0.926	0.924
1130DX	1.191	-	-	-	1.238	-	-	-
Average	1.063	1.025	0.998	1.019	1.059	1.010	0.998	1.022
Stdv	0.073	0.043	0.083	0.079	0.096	0.051	0.079	0.090

Table 4.9 End and Total Deflections
Type B Specimens, P = 16.7 k

Specimen	Ave. End Defl. (inches)			Ave. Total Defl. (inches)		
	Cycle Number			Cycle Number		
	2	100000	450000	2	100000	450000
U11241	0.424	0.464	0.494	0.501	0.433	0.476
E11241	0.451	0.478	0.507	0.511	0.467	0.496
U11242	0.409	0.437	0.480	0.467	0.416	0.450
E11242	0.412	0.432	0.452	0.470	0.433	0.455
U11243	0.428	0.473	0.500	0.529	0.458	0.513
E11243	0.447	0.484	0.511	0.517	0.466	0.509
U11301	0.426	0.461	0.484	0.489	0.448	0.485
E11301	0.426	0.452	0.482	0.486	0.446	0.473
U11302	0.414	0.446	0.475	0.489	0.439	0.472
E11302	0.431	0.468	0.502	0.547	0.452	0.493
U11303	0.387	0.457	0.514	0.530	0.407	0.482
E11303	0.412	0.465	-	-	0.426	0.484
U1130SX	0.414	0.442	0.480	0.495	0.446	0.479
E1130SX	0.414	0.446	0.479	0.490	0.432	0.466
U1130DX	0.438	0.488	0.523	0.570	0.464	0.517
E1130DX	0.500	-	-	-	0.542	-
Ave Unc	0.418	0.459	0.494	0.509	0.439	0.484
Stdev Unc	0.016	0.017	0.018	0.033	0.020	0.022
Ave Epo	0.436	0.461	0.489	0.503	0.458	0.482
Stdev Epo	0.030	0.018	0.022	0.027	0.037	0.019
E/U	1.045	1.005	0.990	0.989	1.044	0.996
						0.984
						0.983

Table 4.10 E/U Ratios of End and Total Deflections
Type B Specimens, P = 16.7 k

Specimen Series	Ave. End Defl. (inches)				Ave. Total Defl. (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
11241	1.063	1.031	1.027	1.020	1.078	1.042	1.037	1.031
11242	1.008	0.989	0.942	1.007	1.040	1.012	0.967	1.032
11243	1.043	1.025	1.021	0.976	1.019	0.992	0.995	0.957
11301	0.999	0.979	0.998	0.994	0.995	0.975	0.992	0.989
11302	1.041	1.048	1.058	1.118	1.031	1.044	1.054	1.117
11303	1.063	1.017	-	-	1.047	1.004	-	-
1130SX	0.999	1.007	0.997	0.989	0.968	0.973	0.965	0.958
1130DX	1.142	-	-	-	1.168	-	-	-
Average	1.045	1.014	1.007	1.017	1.043	1.006	1.002	1.014
Stdev	0.048	0.024	0.039	0.051	0.060	0.029	0.036	0.060

Table 4.11 End and Total Deflections
Type B Specimens, P = Peak Repeating Load

Specimen	Ave. End Defl. (inches)			Ave. Total Defl. (inches)		
	Cycle Number			Cycle Number		
	2	100000	450000	2	100000	450000
U11241	0.424	0.464	0.494	0.501	0.433	0.476
E11241	0.451	0.478	0.507	0.511	0.467	0.496
U11242	0.409	0.437	0.480	0.467	0.416	0.450
E11242	0.412	0.432	0.452	0.470	0.433	0.455
U11243	0.428	0.473	0.500	0.529	0.458	0.513
E11243	0.447	0.484	0.511	0.517	0.466	0.509
U11301	0.518	0.554	0.573	0.579	0.547	0.585
E11301	0.526	0.553	0.572	0.576	0.553	0.582
U11302	0.520	0.538	0.568	0.583	0.553	0.571
E11302	0.536	0.562	0.599	0.643	0.565	0.595
U11303	0.481	0.536	0.592	0.608	0.508	0.567
E11303	0.506	0.549	-	-	0.527	0.573
U1130SX	0.507	0.532	0.565	0.582	0.547	0.576
E1130SX	0.509	0.535	0.566	0.578	0.534	0.562
U1130DX	0.533	0.574	0.610	0.657	0.566	0.610
E1130DX	0.604	-	-	-	0.654	-
Ave Unc	0.477	0.513	0.548	0.563	0.504	0.544
Stdev Unc	0.050	0.049	0.049	0.061	0.060	0.057
Ave Epo	0.499	0.514	0.535	0.549	0.525	0.539
Stdev Epo	0.061	0.049	0.054	0.062	0.070	0.052
E/U	1.045	1.000	0.976	0.975	1.043	0.992

Table 4.12 E/U Ratios of End and Total Deflections
Type B Specimens, P = Peak Repeating Load

Specimen Series	Ave. End Defl. (inches)			Ave. Total Defl. (inches)				
	Cycle Number			Cycle Number				
	2	100000	450000	1000000	2	100000	450000	1000000
11241	1.063	1.031	1.027	1.020	1.078	1.042	1.037	1.031
11242	1.008	0.989	0.942	1.007	1.040	1.012	0.967	1.032
11243	1.043	1.025	1.021	0.976	1.019	0.992	0.995	0.957
11301	1.015	0.999	1.000	0.994	1.011	0.995	0.996	0.990
11302	1.031	1.046	1.055	1.102	1.022	1.042	1.051	1.101
11303	1.053	1.024	-	-	1.038	1.011	-	-
1130SX	1.003	1.005	1.001	0.994	0.976	0.976	0.973	0.967
1130DX	1.134	-	-	-	1.156	-	-	-
Average	1.044	1.017	1.008	1.016	1.042	1.010	1.003	1.013
Stdev	0.042	0.020	0.038	0.045	0.054	0.025	0.034	0.053

**Table 4.13 Summary of Statistics of End and Total Deflections
Type A specimens**

Load	Average and Std. Deviation	Ave. End Defl. (inches)				Ave. Total Defl. (inches)			
		Cycle Number				Cycle Number			
		2	100000	450000	1000000	2	100000	450000	1000000
P = 2 k	Ave Unc	0.489	0.548	0.597	0.626	0.538	0.602	0.654	0.686
	Stdev Unc	0.043	0.058	0.066	0.073	0.049	0.062	0.070	0.078
	Ave Epo	0.520	0.578	0.627	0.645	0.572	0.636	0.695	0.711
	Stdev Epo	0.072	0.084	0.091	0.115	0.081	0.096	0.106	0.131
	E/U	1.064	1.053	1.051	1.031	1.062	1.058	1.063	1.036
P = 3.5 k	Ave Unc	0.662	0.722	0.776	0.808	0.732	0.799	0.855	0.890
	Stdev Unc	0.055	0.069	0.083	0.091	0.062	0.079	0.089	0.097
	Ave Epo	0.698	0.758	0.810	0.824	0.769	0.838	0.899	0.911
	Stdev Epo	0.087	0.101	0.113	0.144	0.098	0.116	0.132	0.164
	E/U	1.054	1.049	1.043	1.019	1.051	1.049	1.052	1.023
P = Peak Rep. Load	Ave Unc	0.825	0.871	0.923	0.957	0.915	0.966	1.020	1.058
	Stdev Unc	0.162	0.169	0.175	0.184	0.185	0.191	0.194	0.203
	Ave Epo	0.868	0.913	0.963	0.938	0.961	1.013	1.073	1.041
	Stdev Epo	0.188	0.196	0.209	0.233	0.214	0.224	0.241	0.265
	E/U	1.052	1.048	1.043	0.981	1.050	1.049	1.052	0.984
Average of	Uncoated	0.659	0.714	0.765	0.797	0.728	0.789	0.843	0.878
	Stdev Unc.	0.087	0.099	0.108	0.116	0.099	0.110	0.118	0.126
	Epoxy-Coated	0.696	0.749	0.800	0.803	0.767	0.829	0.889	0.888
	Stdev Epo	0.116	0.127	0.138	0.164	0.131	0.145	0.160	0.187
	E/U	1.057	1.050	1.046	1.010	1.054	1.052	1.055	1.015

Table 4.14 Summary of E/U Ratios of End and Total Deflections
Type A Specimens

Load	E/U Ratios	Ave. End Defl. (inches)			Ave. Total Defl. (inches)				
		Cycle Number			Cycle Number				
		2	100000	450000	1000000	2	100000	450000	1000000
P = 2 k	Average	1.061	1.051	1.050	1.044	1.059	1.055	1.060	1.046
	Std. Dev	0.082	0.087	0.091	0.100	0.084	0.088	0.092	0.101
P = 3.5 k	Average	1.052	1.048	1.042	1.033	1.049	1.047	1.050	1.034
	Std. Dev	0.072	0.079	0.087	0.096	0.073	0.081	0.087	0.097
P = Peak Rep. Load	Average	1.048	1.045	1.039	1.029	1.046	1.045	1.046	1.031
	Std. Dev	0.074	0.079	0.083	0.098	0.075	0.080	0.084	0.099
Average E/U		1.054	1.048	1.044	1.035	1.051	1.049	1.052	1.037
Ave. Std. Dev		0.076	0.082	0.087	0.098	0.077	0.083	0.088	0.099

Table 4.15 Summary of Statistics of End and Total Deflections
Type B Specimens

Load	Average and Std. Deviation	Ave. End Defl. (inches)			Ave. Total Defl. (inches)		
		Cycle Number			Cycle Number		
		2	100000	450000	2	100000	450000
P = 6 k	Ave Unc	0.222	0.256	0.289	0.303	0.231	0.267
	Stddev Unc	0.013	0.012	0.014	0.025	0.017	0.017
	Ave Epo	0.236	0.259	0.282	0.297	0.244	0.267
	Stddev Epo	0.020	0.015	0.019	0.024	0.027	0.015
	E/U	1.062	1.014	0.975	0.980	1.058	0.998
P = 16.7 k	Ave Unc	0.418	0.459	0.494	0.509	0.439	0.484
	Stddev Unc	0.016	0.017	0.018	0.033	0.020	0.022
	Ave Epo	0.436	0.461	0.489	0.503	0.458	0.482
	Stddev Epo	0.030	0.018	0.022	0.027	0.037	0.019
	E/U	1.045	1.005	0.990	0.989	1.044	0.996
P = Peak Rep. Load	Ave Unc	0.477	0.513	0.548	0.563	0.504	0.544
	Stddev Unc	0.050	0.049	0.049	0.061	0.060	0.057
	Ave Epo	0.499	0.514	0.535	0.549	0.525	0.539
	Stddev Epo	0.061	0.049	0.054	0.062	0.070	0.052
	E/U	1.045	1.000	0.976	0.975	1.043	0.992
Average of	Uncoated	0.372	0.409	0.444	0.458	0.391	0.432
	Stddev Unc.	0.026	0.026	0.027	0.039	0.032	0.032
	Epoxy-Coated	0.390	0.411	0.435	0.450	0.409	0.429
	Stddev Epo	0.037	0.027	0.032	0.038	0.045	0.029
	E/U	1.051	1.006	0.980	0.982	1.048	0.995
						0.975	0.976

Table 4.16 Summary of E/U Ratios of End and Total Deflections
Type B Specimens

Load	E/U Ratios	Ave. End Defl. (inches)				Ave. Total Defl. (inches)			
		Cycle Number				Cycle Number			
		2	100000	450000	1000000	2	100000	450000	1000000
P = 6 k	Average	1.063	1.025	0.998	1.019	1.059	1.010	0.998	1.022
	Std. Dev	0.073	0.043	0.083	0.079	0.096	0.051	0.079	0.090
P = 16.7 k	Average	1.045	1.014	1.007	1.017	1.043	1.006	1.002	1.014
	Std. Dev	0.048	0.024	0.039	0.051	0.060	0.029	0.036	0.060
P = Peak Rep. Load	Average	1.044	1.017	1.008	1.016	1.042	1.010	1.003	1.013
	Std. Dev	0.042	0.020	0.038	0.045	0.054	0.025	0.034	0.053
Average E/U Ave. Std. Dev		1.050	1.019	1.004	1.018	1.048	1.009	1.001	1.016
		0.054	0.029	0.053	0.059	0.070	0.035	0.050	0.068

Table 4.17 Splitting Loads, Failure Loads, and Deflections
Type A Specimens

Specimen	Load (k)			Deflection (inches)		
	Splitting	Failure	Post-Split	Splitting	Failure	Post-Split
U7241	5.50	5.99	0.49	1.237	1.405	0.168
E7241	5.50	5.68	0.18	1.353	1.353	0.000
U7242	7.00	7.07	0.07	1.381	1.410	0.029
E7242	5.75	5.75	0.00	1.197	1.197	0.000
U7301	5.50	6.75	1.25	1.255	1.463	0.208
E7301	5.40	5.40	0.00	1.359	1.359	0.000
U7361	9.20	9.20	0.00	1.818	1.818	0.000
E7361	6.60	6.60	0.00	1.432	1.432	0.000
U7362	8.60	8.80	0.20	1.685	1.685	0.000
E7362	5.50	5.50	0.00	1.267	1.267	0.000
U7363	8.50	9.00	0.50	1.715	1.851	0.136
E7363	6.75	7.50	0.75	1.359	1.507	0.148
U736SX	8.40	8.47	0.07	1.808	1.827	0.018
E736SX	5.50	5.50	0.00	1.320	1.320	0.000
U7STAT	6.50	6.50	0.00	1.250	1.250	0.000
E7STAT	5.00	5.00	0.00	0.980	0.980	0.000
Ave Unc	7.40	7.72	0.32	1.519	1.589	0.070
Stdev Unc	1.47	1.28	0.43	0.262	0.234	0.086
Ave Epo	5.75	5.87	0.12	1.283	1.302	0.019
Stdev Epo	0.61	0.80	0.26	0.141	0.161	0.052
E/U	0.78	0.76	0.36	0.845	0.820	0.265

Table 4.18 E/U Ratios of Load and Deflections at Splitting and Failure load
Type A Specimens

Specimen Series	Load (K)		Deflection (inches)	
	Splitting	Failure	Splitting	Failure
7241	1.00	0.95	1.094	0.963
7242	0.82	0.81	0.867	0.849
7301	0.98	0.80	1.083	0.929
7361	0.72	0.72	0.788	0.788
7362	0.64	0.63	0.752	0.752
7363	0.79	0.83	0.792	0.814
736SX	0.65	0.65	0.730	0.723
7STAT	0.77	0.77	0.784	0.784
Average	0.80	0.77	0.861	0.825
Std. Dev	0.14	0.10	0.146	0.084

Table 4.19 Splitting Loads, Failure Loads, and Deflections
Type B Specimens

Specimen	Load (k)			Deflection (inches)		
	Splitting	Failure	Post-Split	Splitting	Failure	Post-Split
U11241	23.00	30.00	7.00	0.650	0.901	0.251
E11241	20.00	25.56	5.56	0.588	0.787	0.199
U11242	28.00	35.56	7.56	0.637	0.836	0.199
E11242	27.50	28.06	0.56	0.704	0.795	0.091
U11243	20.00	32.24	12.24	0.660	1.079	0.419
E11243	23.18	26.12	2.94	0.688	0.776	0.088
U11301	24.00	40.00	16.00	0.642	1.120	0.478
E11301	22.00	29.88	7.88	0.594	0.854	0.260
U11302	25.00	38.01	13.01	0.645	1.095	0.450
E11302	22.00	28.74	6.74	0.652	0.847	0.195
U11303	27.29	37.00	9.71	0.763	1.096	0.333
E11303	21.25	21.25	0.00	0.528	0.614	0.086
U1130SX	32.02	42.03	10.01	0.879	1.243	0.364
E1130SX	23.00	32.00	9.00	0.641	0.849	0.208
U1130DX	21.30	34.00	12.70	0.701	1.084	0.383
E1130DX	21.39	21.39	0.00	0.657	0.657	0.000
U11STAT	25.00	32.60	7.60	0.628	0.924	0.296
E11STAT	21.77	25.36	3.59	0.558	0.673	0.115
Ave Unc	25.07	35.72	10.65	0.689	1.042	0.353
Stdev Unc	3.66	3.91	3.05	0.083	0.128	0.092
Ave Epo	22.45	26.48	4.03	0.623	0.761	0.138
Stdev Epo	2.11	3.63	3.45	0.060	0.091	0.082
E/U	0.90	0.74	0.38	0.904	0.731	0.391

Table 4.20 E/U Ratios of Load and Deflection at Splitting and Failure Load
Type B Specimens

Specimen Series	Load (K)		Deflection (inches)	
	Splitting	Failure	Splitting	Failure
11241	0.87	0.85	0.905	0.873
11242	0.98	0.79	1.105	0.951
11243	1.16	0.81	1.042	0.719
11301	0.92	0.75	0.925	0.763
11302	0.88	0.76	1.011	0.774
11303	0.78	0.57	0.692	0.560
1130SX	0.72	0.76	0.729	0.683
1130DX	1.00	0.63	0.936	0.606
Average	0.91	0.74	0.918	0.741
Std. Dev	0.14	0.09	0.145	0.130

Table 4.21 Ratio of Post-Splitting Load and Deflection versus Splitting Load and Deflection

Specimens	Bars	Average Load (k)			Average Deflection (inches)			Post-Split/ Split Ratio	
		Splitting	Failure	Post -Split	Splitting	Failure	Post-Split	Load	Deflection
Type A	U	7.40	7.72	0.32	1.519	1.589	0.070	4.36%	4.60%
	E	5.75	5.87	0.12	1.283	1.302	0.019	2.02%	1.44%
Type B	U	25.07	35.72	10.65	0.689	1.042	0.353	42.48%	51.14%
	E	22.45	26.48	4.03	0.623	0.761	0.138	17.95%	22.14%

Table 4.22 Peak Stress, Splitting Deflection, and Failure Deflection

Deflection at :		Type A Specimens			Type B Specimens		
		Series vs Series		Note	Series vs Series		Note
		7241+7242	7361+7362		11241+11242	11301+11302	
Splitting	U	1.309	1.752	*	0.644	0.644	***
	E	1.275	1.350	*	0.646	0.623	**
Failure	U	1.408	1.752	*	0.869	1.108	*
	E	1.275	1.350	*	0.791	0.851	*
		7241	7301		11243	11303	
Splitting	U	1.237	1.255	*	0.660	0.763	*
	E	1.353	1.359	*	0.688	0.528	**
Failure	U	1.405	1.463	*	1.079	1.096	*
	E	1.353	1.359	*	0.776	0.614	**
		7301	7361+7362				
Splitting	U	1.255	1.752	*			
	E	1.359	1.350	**			
Failure	U	1.463	1.752	*			
	E	1.359	1.350	**			

* lower peak stress, smaller deflection

** lower peak stress, larger deflection

*** same

Table 4.23 Stress Range, Splitting Deflection, and Failure Deflection

Deflection at :		Type A Specimens			Type B Specimens				
		Series vs Series		Note	Series vs Series		Note		
		7241 + 7242 7301 + 7361 7362	7363		11241 + 11242 11243				
Splitting	U	1.475	1.715	*	Neglect	0.644	0.660	*	Same Peak
	E	1.322	1.359	*	Peak Stress	0.646	0.688	*	Stress
Failure	U	1.556	1.851	*	Neglect f'c	0.869	1.079	*	Neglect f'c
	E	1.322	1.507	*		0.791	0.776	**	
		7361 + 7362	7363			11301 + 11302	11303		
Splitting	U	1.752	1.715	**	Same Peak	0.644	0.763	*	Same Peak
	E	1.350	1.359	*	Stress	0.623	0.528	**	Stress
Failure	U	1.752	1.851	*	Same f'c	1.108	1.096	**	Neglect f'c
	E	1.350	1.507	*		0.851	0.614	**	

* lower stress range, smaller deflection

** lower stress range, larger deflection

Table 4.24 Coating Thickness and Deformation Pattern

Specimens	Bars	Deflection (inches)				Average Load (k)			Average Deflection (inches)			
		Cycle Number				Splitting	Failure	Post -Split	Splitting	Failure	Post-Split	
		2	100000	450000	1000000							
Type A	7361 +	U	0.983	1.024	1.070	1.111	8.90	9.00	0.10	1.752	1.752	0.00
	7362	E	1.086	1.140	1.209	1.165	6.05	6.05	0.00	1.350	1.350	0.00
		E/U	1.105	1.113	1.130	1.049	0.68	0.67	-	0.771	0.771	-
	736SX	U	1.137	1.201	1.257	1.294	8.40	8.47	0.07	1.808	1.827	0.02
		E	1.164	1.213	1.318	-	5.50	5.50	0.00	1.320	1.320	0.00
		E/U	1.024	1.010	1.049	-	0.65	0.65	-	0.730	0.722	-
Type B	11301 +	U	0.550	0.578	0.604	0.616	24.50	39.01	14.51	0.644	1.108	0.46
	11302	E	0.559	0.589	0.618	0.645	22.00	29.31	7.31	0.623	0.851	0.23
		E/U	1.016	1.019	1.023	1.047	0.90	0.75	-	0.967	0.768	-
	1130SX	U	0.547	0.576	0.640	0.630	32.02	42.03	10.01	0.879	1.243	0.36
		E	0.534	0.562	0.595	0.609	23.00	32.00	9.00	0.641	0.849	0.21
		E/U	0.976	0.976	0.930	0.967	0.72	0.76	-	0.729	0.683	-
	1130DX	U	0.566	0.610	0.650	0.701	21.30	34.00	12.70	0.701	1.084	0.38
		E	0.654	-	-	-	21.39	21.39	0.00	0.657	0.657	0.00
		E/U	1.155	-	-	-	1.00	0.63	-	0.937	0.606	-

Table 4.25 Number of Cracks in the Constant Moment Region at Failure

Specimen	Before Failure Cycle			At Failure Cycle			Specimen	Before Failure Cycle			At Failure Cycle		
	Outside	Inside	Total	Outside	Inside	Total		Outside	Inside	Total	Outside	Inside	Total
U7241	3	5	8	3	5	8	U11241	2	4	6	2	4	6
E7241	5	2	7	5	3	8	E11241	2	4	6	2	4	6
U7242	4	2	6	4	2	6	U11242	4	3	7	4	4	8
E7242	3	1	4	4	2	7	E11242	2	5	7	2	6	8
U7301	4	2	6	4	3	7	U11243	2	5	7	3	8	11
E7301	4	2	6	4	3	7	E11243	2	5	7	2	6	8
U7361	4	2	6	5	2	7	U11301	2	5	7	2	7	9
E7361	4	2	6	4	2	6	E11301	2	6	8	3	6	9
U7362	4	2	6	4	3	7	U11302	1	5	6	3	7	10
E7362	2	2	4	2	3	5	E11302	1	4	5	3	6	9
U7363	4	2	6	4	2	6	U11303	3	4	7	4	5	9
E7363	4	2	6	5	2	7	E11303	4	3	7	5	4	9
U736SX	4	2	6	4	2	6	U1130SX	2	4	6	3	6	9
E736SX	4	1	5	4	1	5	E1130SX	4	4	8	5	4	9
U7STAT	4	3	7	5	3	8	U1130DX	2	6	8	3	6	9
E7STAT	4	1	5	4	3	7	E1130DX	2	4	6	4	4	8
							U11STAT	2	5	7	2	5	7
							E11STAT	2	5	7	3	6	9
Ave. Unc	3.88	2.50	6.38	4.13	2.75	6.88	Ave. Unc	2.25	4.50	6.75	3.00	5.88	8.88
Ave. Epo	3.75	1.63	5.38	4.00	2.38	6.50	Ave. Epo	2.38	4.38	6.75	3.25	5.00	8.25
E/U	0.968	0.650	0.843	0.970	0.864	0.945	E/U	1.056	0.972	1.000	1.083	0.851	0.930

Table 4.26 Cracking Loads

Type A Specimens				Type B Specimens			
Specimen	First Crack	First Split	E/U Ratio	Specimen	First Crack	First Split	E/U Ratio
	(kips)	(kips)	Flexure Splitting		(kips)	(kips)	Flexure Splitting
U7241	2.00	5.50	0.500 1.000	U11241	5.00	23.00	0.720 0.870
E7241	1.00	5.50		E11241	3.60	20.00	
U7242	1.40	7.00	1.071 0.821	U11242	3.00	28.00	1.233 0.982
E7242	1.50	5.75		E11242	3.70	27.50	
U7301	1.30	5.50	0.923 0.982	U11243	5.00	20.00	0.600 1.159
E7301	1.20	5.40		E11243	3.00	23.18	
U7361	2.00	9.20	0.850 0.717	U11301	4.00	24.00	1.000 0.917
E7361	1.70	6.60		E11301	4.00	22.00	
U7362	2.50	8.50	0.600 0.647	U11302	3.00	25.00	1.333 0.880
E7362	1.50	5.50		E11302	4.00	22.00	
U7363	1.50	8.50	1.333 0.794	U11303	4.00	27.29	1.000 0.779
E7363	2.00	6.75		E11303	4.00	21.25	
U736SX	1.80	8.40	1.111 0.655	U1130SX	3.50	32.02	1.143 0.718
E736SX	2.00	5.50		E1130SX	4.00	23.00	
				U1130DX	4.00	21.30	0.500 1.004
				E1130DX	2.00	21.39	
Ave Unc	1.786	7.367		Ave Unc	3.938	25.076	
Stdv Unc	0.422	1.525		Stdv Unc	0.776	3.913	
Ave Epo	1.557	5.857		Ave Epo	3.538	22.540	
Stdv Epo	0.378	0.570		Stdv Epo	0.711	2.244	
Ave E/U	0.872	0.795	0.913 0.802	Ave E/U	0.898	0.899	0.941 0.914

Table 4.27 Crack Widths in Constant Moment Region
Type A Specimens, $P = 2\text{ k}$

Specimen	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
U7241	0.043	0.050	0.059	0.070	0.005	0.006	0.007	0.009
E7241	0.053	0.052	0.065	0.069	0.008	0.007	0.009	0.010
U7242	0.062	0.063	0.069	0.072	0.010	0.010	0.012	0.012
E7242	0.050	0.060	0.067	0.070	0.013	0.015	0.017	0.018
U7301	0.088	0.095	0.104	0.114	0.015	0.016	0.017	0.019
E7301	0.095	0.108	0.120	0.129	0.016	0.018	0.020	0.022
U7361	0.071	0.081	0.088	0.094	0.012	0.013	0.015	0.016
E7361	0.067	0.075	0.081	0.091	0.011	0.013	0.014	0.015
U7362	0.074	0.084	0.093	0.095	0.012	0.014	0.015	0.016
E7362	0.059	0.067	0.080	-	0.015	0.017	0.020	-
U7363	0.059	0.077	0.080	0.085	0.010	0.013	0.013	0.014
E7363	0.092	0.100	0.111	0.121	0.015	0.017	0.018	0.020
U736SX	0.067	0.078	0.088	0.096	0.011	0.013	0.015	0.016
E736SX	0.074	0.080	0.092	-	0.015	0.016	0.018	-
Ave Unc	0.066	0.075	0.083	0.089	0.011	0.012	0.013	0.014
Stdev Unc	0.014	0.015	0.015	0.015	0.003	0.003	0.003	0.003
Ave Epo	0.070	0.077	0.088	0.096	0.013	0.015	0.017	0.017
Stdev Epo	0.018	0.021	0.021	0.028	0.003	0.004	0.004	0.005
E/U	1.056	1.026	1.061	1.073	1.217	1.190	1.234	1.161

Table 4.28 E/U Ratios of Crack Widths in Constant Moment Region
Type A Specimens, $P = 2 \text{ k}$

Specimen Series	Total Crack Width (inches)				Ave. Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
7241	1.233	1.044	1.106	0.990	1.409	1.193	1.264	1.131
7242	0.806	0.945	0.971	0.972	1.210	1.417	1.457	1.458
7301	1.080	1.137	1.154	1.132	1.080	1.137	1.154	1.132
7361	0.944	0.929	0.920	0.963	0.944	0.929	0.920	0.963
7362	0.797	0.798	0.863	-	1.196	1.196	1.294	-
7363	1.559	1.299	1.388	1.424	1.559	1.299	1.388	1.424
736SX	1.104	1.023	1.043	-	1.325	1.227	1.252	-
Average	1.075	1.025	1.064	1.096	1.246	1.200	1.247	1.222
Std. Dev	0.267	0.161	0.176	0.195	0.206	0.150	0.174	0.212

Table 4.29 Crack Widths in the Constant Moment Region Outside the Splice
Type A Specimens, $P = 2 \text{ k}$

Specimen	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
U7241	0.020	0.022	0.025	0.028	0.007	0.007	0.008	0.009
E7241	0.045	0.043	0.053	0.055	0.009	0.009	0.011	0.011
U7242	0.047	0.048	0.053	0.054	0.012	0.012	0.013	0.014
E7242	0.040	0.049	0.055	0.056	0.013	0.016	0.018	0.019
U7301	0.063	0.067	0.072	0.078	0.016	0.017	0.018	0.020
E7301	0.066	0.073	0.079	0.084	0.017	0.018	0.020	0.021
U7361	0.057	0.064	0.070	0.074	0.014	0.016	0.018	0.019
E7361	0.050	0.056	0.060	0.068	0.013	0.014	0.015	0.017
U7362	0.051	0.057	0.063	0.063	0.013	0.014	0.016	0.016
E7362	0.034	0.034	0.036	-	0.017	0.017	0.018	-
U7363	0.044	0.062	0.062	0.065	0.011	0.016	0.015	0.016
E7363	0.077	0.080	0.087	0.096	0.019	0.020	0.022	0.024
U736SX	0.045	0.051	0.056	0.062	0.011	0.013	0.014	0.016
E736SX	0.055	0.057	0.063	-	0.014	0.014	0.016	-
Ave Unc	0.047	0.053	0.057	0.061	0.012	0.014	0.015	0.015
Stdev Unc	0.014	0.015	0.016	0.017	0.003	0.003	0.003	0.003
Ave Epo	0.052	0.056	0.062	0.072	0.015	0.016	0.017	0.018
Stdev Epo	0.015	0.016	0.017	0.018	0.003	0.004	0.004	0.005
E/U	1.122	1.056	1.081	1.186	1.218	1.150	1.166	1.186

Table 4.31 Crack Widths Inside the Splice
Type A Specimens, P = 2 K

Specimen	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	10000	45000	100000	2	10000	45000	100000
U7241	0.023	0.028	0.034	0.042	0.005	0.006	0.007	0.008
E7241	0.008	0.009	0.012	0.014	0.004	0.005	0.006	0.007
U7242	0.015	0.015	0.016	0.018	0.008	0.008	0.008	0.009
E7242	0.010	0.011	0.012	0.014	0.010	0.011	0.012	0.014
U7301	0.025	0.028	0.032	0.036	0.013	0.014	0.016	0.018
E7301	0.029	0.035	0.041	0.045	0.015	0.018	0.020	0.023
U7361	0.014	0.017	0.018	0.020	0.007	0.008	0.009	0.010
E7361	0.017	0.019	0.021	0.023	0.009	0.010	0.011	0.011
U7362	0.023	0.027	0.030	0.032	0.012	0.014	0.015	0.016
E7362	0.025	0.033	0.044	-	0.009	0.015	0.019	-
U7363	0.015	0.015	0.018	0.020	0.008	0.008	0.009	0.010
E7363	0.015	0.020	0.024	0.025	0.008	0.010	0.012	0.013
U736SX	0.022	0.027	0.032	0.034	0.011	0.014	0.016	0.017
E736SX	0.019	0.023	0.029	-	0.019	0.023	0.029	-
Ave Unc	0.020	0.022	0.026	0.029	0.009	0.010	0.011	0.013
Stdev Unc	0.005	0.006	0.008	0.009	0.003	0.004	0.004	0.004
Ave Epo	0.018	0.021	0.026	0.024	0.010	0.013	0.016	0.013
Stdev Epo	0.008	0.010	0.013	0.013	0.005	0.006	0.008	0.006
E/U	0.898	0.956	1.017	0.835	1.177	1.291	1.364	1.065

Table 4.32 E/U Ratios of Crack Widths Inside the Splice
Type A Specimens, P = 2 K

Specimen Series	Total Crack Width (inches)				Ave. Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
7241	0.348	0.323	0.355	0.333	0.870	0.808	0.888	0.831
7242	0.667	0.730	0.750	0.778	1.333	1.460	1.500	1.556
7301	1.160	1.250	1.281	1.250	1.160	1.250	1.281	1.250
7361	1.214	1.123	1.167	1.125	1.214	1.123	1.167	1.125
7362	1.087	1.222	1.467	-	0.783	1.111	1.267	-
7363	1.000	1.333	1.334	1.250	1.000	1.333	1.334	1.250
736SX	0.864	0.848	0.900	-	1.727	1.697	1.801	-
Average	0.906	0.976	1.036	0.947	1.155	1.255	1.320	1.202
Std. Dev	0.309	0.362	0.391	0.394	0.318	0.283	0.282	0.261

Table 4.33 Crack Widths in Constant Moment Region
Type A Specimens, P = 3.5 k

Specimen	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
U7241	0.069	0.072	0.087	0.089	0.009	0.009	0.011	0.011
E7241	0.083	0.078	0.087	0.093	0.012	0.011	0.012	0.013
U7242	0.082	0.086	0.090	0.095	0.014	0.014	0.015	0.016
E7242	0.077	0.079	0.084	0.090	0.019	0.020	0.021	0.023
U7301	0.117	0.313	0.360	0.365	0.020	0.052	0.060	0.061
E7301	0.130	0.138	0.148	0.155	0.022	0.023	0.025	0.026
U7361	0.100	0.111	0.114	0.124	0.017	0.018	0.019	0.021
E7361	0.099	0.098	0.110	0.117	0.017	0.016	0.018	0.020
U7362	0.102	0.109	0.120	0.124	0.017	0.018	0.020	0.021
E7362	0.080	0.086	0.102	-	0.020	0.022	0.026	-
U7363	0.083	0.089	0.099	0.108	0.014	0.015	0.016	0.018
E7363	0.125	0.130	0.146	0.156	0.021	0.022	0.024	0.026
U736SX	0.090	0.111	0.118	0.122	0.015	0.019	0.020	0.020
E736SX	0.100	0.108	0.119	-	0.020	0.022	0.024	-
Ave Unc	0.092	0.127	0.141	0.147	0.015	0.021	0.023	0.024
Stdev Unc	0.016	0.083	0.097	0.097	0.003	0.014	0.017	0.017
Ave Epo	0.099	0.102	0.114	0.122	0.019	0.019	0.021	0.021
Stdev Epo	0.021	0.024	0.026	0.032	0.003	0.004	0.005	0.005
E/U	1.079	0.805	0.806	0.833	1.248	0.928	0.932	0.896

Table 4.34 E/U Ratios of Crack Widths in Constant Moment Region
Type A Specimens, $P = 3.5 \text{ k}$

Specimen Series	Total Crack Width (inches)				Ave. Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
7241	1.203	1.085	1.001	1.050	1.375	1.240	1.144	1.200
7242	0.939	0.918	0.933	0.947	1.409	1.377	1.400	1.421
7301	1.111	0.441	0.411	0.425	1.111	0.441	0.411	0.425
7361	0.990	0.885	0.965	0.944	0.990	0.885	0.965	0.944
7362	0.784	0.789	0.851	-	1.176	1.183	1.277	-
7363	1.506	1.461	1.475	1.444	1.506	1.461	1.475	1.444
736SX	1.111	0.972	1.006	-	1.333	1.166	1.207	-
Average	1.092	0.936	0.949	0.962	1.271	1.108	1.125	1.087
Std. Dev	0.228	0.308	0.311	0.364	0.184	0.346	0.357	0.422

Table 4.35 Crack Widths in the Constant Moment Region Outside the Splice
Type A Specimens, $P = 3.5 \text{ k}$

Specimen	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
U7241	0.029	0.030	0.036	0.037	0.010	0.010	0.012	0.012
E7241	0.070	0.064	0.071	0.075	0.014	0.013	0.014	0.015
U7242	0.061	0.065	0.036	0.071	0.015	0.016	0.012	0.071
E7242	0.062	0.064	0.068	0.072	0.021	0.021	0.023	0.024
U7301	0.082	0.274	0.320	0.322	0.021	0.069	0.080	0.081
E7301	0.094	0.094	0.099	0.103	0.024	0.024	0.025	0.026
U7361	0.079	0.088	0.091	0.098	0.020	0.022	0.023	0.025
E7361	0.073	0.072	0.082	0.086	0.018	0.018	0.020	0.022
U7362	0.072	0.073	0.081	0.085	0.018	0.018	0.020	0.021
E7362	0.044	0.044	0.047	-	0.022	0.022	0.024	-
U7363	0.065	0.070	0.076	0.084	0.016	0.018	0.019	0.021
E7363	0.102	0.104	0.114	0.122	0.026	0.026	0.028	0.031
U736SX	0.063	0.075	0.078	0.081	0.016	0.019	0.020	0.020
E736SX	0.076	0.078	0.083	-	0.019	0.020	0.021	-
Ave Unc	0.064	0.096	0.103	0.111	0.016	0.024	0.026	0.036
Stdev Unc	0.018	0.080	0.098	0.095	0.004	0.020	0.024	0.028
Ave Epo	0.074	0.074	0.081	0.092	0.020	0.020	0.022	0.023
Stdev Epo	0.019	0.020	0.022	0.021	0.004	0.004	0.004	0.006
E/U	1.155	0.771	0.786	0.824	1.241	0.836	0.835	0.652

Table 4.36 E/U Ratios of Crack Widths in the Constant Moment Region Outside the Splice
Type A Specimens, $P = 3.5 \text{ k}$

Specimen Series	Total Crack Width (inches)				Ave. Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
7241	2.414	2.135	1.973	2.027	1.448	1.281	1.184	1.216
7242	1.016	0.984	1.890	1.014	1.355	1.312	1.890	0.338
7301	1.146	0.343	0.310	0.320	1.146	0.343	0.310	0.320
7361	0.924	0.821	0.901	0.878	0.924	0.821	0.901	0.878
7362	0.611	0.603	0.582	-	1.222	1.205	1.163	-
7363	1.569	1.486	1.500	1.452	1.569	1.486	1.500	1.452
736SX	1.206	1.040	1.063	-	1.206	1.040	1.063	-
Average	1.270	1.059	1.174	1.138	1.267	1.070	1.144	0.841
Std. Dev	0.582	0.595	0.638	0.641	0.212	0.384	0.491	0.510

Table 4.37 Crack Widths Inside the Splice
Type A Specimens, P = 3.5 K

Specimen	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	10000	45000	100000	2	10000	45000	100000
U7241	0.040	0.042	0.051	0.052	0.008	0.008	0.010	0.010
E7241	0.013	0.014	0.016	0.018	0.007	0.007	0.008	0.009
U7242	0.021	0.021	0.022	0.024	0.011	0.011	0.011	0.012
E7242	0.015	0.015	0.016	0.018	0.015	0.015	0.016	0.018
U7301	0.035	0.039	0.040	0.043	0.018	0.020	0.020	0.022
E7301	0.036	0.044	0.049	0.052	0.018	0.022	0.025	0.026
U7361	0.021	0.023	0.023	0.026	0.011	0.011	0.012	0.013
E7361	0.026	0.026	0.028	0.031	0.013	0.013	0.014	0.016
U7362	0.030	0.036	0.039	0.039	0.015	0.018	0.020	0.020
E7362	0.036	0.042	0.055	-	0.015	0.018	0.024	-
U7363	0.018	0.019	0.023	0.024	0.009	0.010	0.011	0.012
E7363	0.023	0.026	0.032	0.034	0.012	0.013	0.016	0.017
U736SX	0.027	0.036	0.040	0.041	0.014	0.018	0.020	0.021
E736SX	0.024	0.030	0.036	-	0.024	0.030	0.036	-
Ave Unc	0.027	0.031	0.034	0.036	0.012	0.014	0.015	0.016
Stdev Unc	0.008	0.010	0.011	0.011	0.003	0.005	0.005	0.005
Ave Epo	0.025	0.028	0.033	0.031	0.015	0.017	0.020	0.017
Stdev Epo	0.009	0.012	0.015	0.014	0.005	0.007	0.009	0.006
E/U	0.901	0.912	0.974	0.862	1.226	1.237	1.333	1.100

Table 4.38 E/U Ratios of Crack Widths Inside the Splice
Type A Specimens, P = 3.5 K

Specimen Series	Total Crack Width (inches)				Ave. Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	10000	45000	100000	2	10000	45000	100000
7241	0.325	0.334	0.314	0.349	0.813	0.834	0.785	0.872
7242	0.714	0.714	0.727	0.750	1.429	1.429	1.455	1.500
7301	1.029	1.128	1.225	1.209	1.029	1.128	1.225	1.209
7361	1.238	1.133	1.217	1.192	1.238	1.133	1.217	1.192
7362	1.200	1.167	1.410	-	1.000	1.000	1.231	-
7363	1.278	1.368	1.392	1.417	1.278	1.368	1.392	1.417
736SX	0.889	0.831	0.894	-	1.778	1.662	1.788	-
Average	0.953	0.954	1.026	0.983	1.223	1.222	1.299	1.238
Std. Dev	0.344	0.350	0.402	0.430	0.319	0.281	0.303	0.244

Table 4.39 Crack Widths in Constant Moment Region
Type A Specimens, P = Peak Repeating Load

Specimen	Total				Average			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
U7241	0.069	0.072	0.087	0.089	0.009	0.009	0.011	0.011
E7241	0.083	0.078	0.087	0.093	0.012	0.011	0.012	0.013
U7242	0.082	0.086	0.090	0.095	0.014	0.014	0.015	0.016
E7242	0.077	0.079	0.084	0.090	0.019	0.020	0.021	0.023
U7301	0.134	0.139	0.150	0.160	0.022	0.023	0.025	0.027
E7301	0.152	0.159	0.168	0.179	0.025	0.027	0.028	0.030
U7361	0.134	0.145	0.152	0.161	0.022	0.024	0.025	0.027
E7361	0.129	0.135	0.146	0.160	0.022	0.023	0.024	0.027
U7362	0.145	0.149	0.155	0.158	0.024	0.025	0.026	0.026
E7362	0.103	0.111	0.128	-	0.026	0.028	0.032	-
U7363	0.114	0.116	0.129	0.136	0.019	0.019	0.022	0.023
E7363	0.179	0.177	0.193	0.203	0.030	0.030	0.032	0.034
U736SX	0.136	0.141	0.154	0.160	0.023	0.024	0.026	0.027
E736SX	0.135	0.143	0.155	-	0.027	0.029	0.031	-
Ave Unc	0.116	0.121	0.131	0.137	0.019	0.020	0.021	0.022
Stdev Unc	0.030	0.031	0.030	0.032	0.006	0.006	0.006	0.006
Ave Epo	0.123	0.126	0.137	0.145	0.023	0.024	0.026	0.025
Stdev Epo	0.037	0.038	0.041	0.051	0.006	0.007	0.007	0.008
E/U	1.054	1.040	1.047	1.059	1.209	1.198	1.212	1.131

Table 4.40 E/U Ratios of Crack Widths in Constant Moment Region
Type A Specimens, P = Peak Repeating Load

Specimen Series	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
7241	1.203	1.085	1.001	1.050	1.375	1.240	1.144	1.200
7242	0.939	0.918	0.933	0.947	1.409	1.377	1.400	1.421
7301	1.134	1.144	1.120	1.119	1.134	1.144	1.120	1.119
7361	0.963	0.933	0.957	0.994	0.963	0.933	0.957	0.994
7362	0.710	0.745	0.827	-	1.066	1.117	1.240	-
7363	1.570	1.526	1.495	1.493	1.570	1.526	1.495	1.493
736SX	0.993	1.012	1.005	-	1.191	1.214	1.206	-
Average	1.073	1.052	1.048	1.120	1.244	1.222	1.223	1.245
Ste. Dev	0.149	0.051	0.003	0.218	0.130	0.018	0.044	0.208

Table 4.41 Crack Widths in the Constant Moment Region Outside the Splice
Type A Specimens, P = Peak Repeating Load

Specimen	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
U7241	0.029	0.030	0.036	0.037	0.010	0.010	0.012	0.012
E7241	0.070	0.064	0.071	0.075	0.014	0.013	0.014	0.015
U7242	0.061	0.065	0.036	0.071	0.015	0.016	0.012	0.071
E7242	0.062	0.064	0.068	0.072	0.021	0.021	0.023	0.024
U7301	0.094	0.098	0.104	0.109	0.024	0.025	0.026	0.027
E7301	0.107	0.110	0.115	0.120	0.027	0.028	0.029	0.030
U7361	0.105	0.114	0.120	0.128	0.026	0.028	0.030	0.032
E7361	0.096	0.100	0.110	0.119	0.024	0.025	0.027	0.030
U7362	0.100	0.101	0.104	0.105	0.025	0.025	0.026	0.026
E7362	0.054	0.058	0.060	-	0.027	0.029	0.030	-
U7363	0.089	0.090	0.099	0.105	0.022	0.023	0.025	0.026
E7363	0.143	0.140	0.151	0.158	0.036	0.035	0.038	0.040
U736SX	0.091	0.094	0.100	0.106	0.023	0.024	0.025	0.027
E736SX	0.102	0.106	0.112	-	0.026	0.027	0.028	-
Ave Unc	0.081	0.085	0.086	0.094	0.021	0.021	0.022	0.032
Stdev Unc	0.027	0.028	0.035	0.030	0.006	0.006	0.007	0.018
Ave Epo	0.091	0.092	0.098	0.109	0.025	0.025	0.027	0.028
Stdev Epo	0.031	0.031	0.033	0.036	0.007	0.007	0.007	0.009
E/U	1.114	1.084	1.146	1.152	1.200	1.176	1.212	0.873

Table 4.42 E/U Ratios of Crack Widths in the Constant Moment Region Outside the Splice
Type A Specimens, P = Peak Repeating Load

Specimen Series	Total Crack Width (inches)				Ave. Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
7241	2.414	2.135	1.973	2.027	1.448	1.281	1.184	1.216
7242	1.016	0.984	1.890	1.014	1.355	1.312	1.890	0.338
7301	1.138	1.122	1.106	1.101	1.138	1.122	1.106	1.101
7361	0.914	0.875	0.913	0.930	0.914	0.875	0.913	0.930
7362	0.540	0.574	0.578	-	1.080	1.149	1.156	-
7363	1.607	1.556	1.524	1.505	1.607	1.556	1.524	1.505
736SX	1.121	1.126	1.118	-	1.121	1.126	1.118	-
Average	1.250	1.196	1.300	1.315	1.238	1.203	1.270	1.018
Std. Dev	0.603	0.509	0.515	0.455	0.241	0.210	0.328	0.434

Table 4.43 Crack Widths Inside the Splice
Type A Specimens, P = Peak Repeating Load

Specimen	Total Crack Width (inches)			Average Crack Width (inches)				
	Cycle Number			Cycle Number				
	2	10000	45000	100000	2	10000	45000	100000
U7241	0.040	0.042	0.051	0.052	0.008	0.008	0.010	0.010
E7241	0.013	0.014	0.016	0.018	0.007	0.007	0.008	0.009
U7242	0.021	0.021	0.022	0.024	0.011	0.011	0.011	0.012
E7242	0.015	0.015	0.016	0.018	0.015	0.015	0.016	0.018
U7301	0.040	0.042	0.046	0.051	0.008	0.008	0.023	0.026
E7301	0.045	0.049	0.053	0.059	0.023	0.025	0.026	0.030
U7361	0.029	0.031	0.032	0.033	0.015	0.015	0.016	0.017
E7361	0.033	0.036	0.036	0.041	0.017	0.018	0.018	0.021
U7362	0.045	0.048	0.051	0.053	0.023	0.024	0.026	0.027
E7362	0.049	0.053	0.068	-	0.021	0.023	0.029	-
U7363	0.025	0.026	0.030	0.031	0.013	0.013	0.015	0.016
E7363	0.036	0.037	0.042	0.045	0.018	0.019	0.021	0.023
U736SX	0.045	0.047	0.054	0.054	0.023	0.024	0.027	0.027
E736SX	0.033	0.037	0.043	-	0.033	0.037	0.043	-
Ave Unc	0.035	0.037	0.041	0.043	0.014	0.015	0.018	0.019
Stdev Unc	0.010	0.011	0.013	0.013	0.006	0.007	0.007	0.007
Ave Epo	0.032	0.034	0.039	0.036	0.019	0.020	0.023	0.020
Stdev Epo	0.014	0.015	0.019	0.018	0.008	0.009	0.011	0.007
E/U	0.914	0.936	0.958	0.851	1.345	1.383	1.265	1.045

Table 4.45 Crack Widths in Constant Moment Region
Type B Specimens, $P = 6 \text{ k}$

Specimen	Total Crack Width (inches)			Average Crack Width (inches)		
	Cycle Number			Cycle Number		
	2	10000	45000	100000	45000	100000
U11241	0.0290	0.0310	0.0380	0.0410	0.0041	0.0054
E11241	0.0290	0.0319	0.0385	0.0410	0.0048	0.0068
U11242	0.0300	0.0330	0.0439	0.0420	0.0060	0.0063
E11242	0.0340	0.0389	0.0440	0.0490	0.0068	0.0073
U11243	0.0240	0.0330	0.0418	0.0480	0.0034	0.0060
E11243	0.0390	0.0440	0.0540	0.0540	0.0065	0.0090
U11301	0.0240	0.0300	0.0350	0.0350	0.0034	0.0050
E11301	0.0390	0.0430	0.0455	0.0480	0.0049	0.0057
U11302	0.0250	0.0270	0.0309	0.0350	0.0042	0.0051
E11302	0.0300	0.0340	0.0439	0.0440	0.0060	0.0088
U11303	0.0330	0.0390	0.0468	0.0540	0.0047	0.0067
E11303	0.0420	0.0540	-	-	0.0060	-
U1130SX	0.0270	0.0280	0.0330	0.0348	0.0045	0.0058
E1130SX	0.0330	0.0400	0.0480	0.0520	0.0041	0.0065
U1130DX	0.0320	0.0390	0.0450	0.0500	0.0040	0.0063
E1130DX	0.0330	0.0540	-	-	0.0055	-
Ave Unc	0.0280	0.0325	0.0393	0.0425	0.0043	0.0057
Stdev Unc	0.0035	0.0045	0.0059	0.0075	0.0008	0.0008
Ave Epo	0.0349	0.0425	0.0456	0.0480	0.0056	0.0072
Stdev Epo	0.0046	0.0082	0.0051	0.0049	0.0009	0.0012
E/U	1.246	1.307	1.161	1.130	1.298	1.193

Table 4.46 E/U Ratios of Crack Widths in Constant Moment Region
Type B Specimens, $P = 6 \text{ k}$

Specimen Series	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
11241	1.000	1.030	1.013	1.000	1.167	1.202	1.182	1.167
11242	1.133	1.178	1.002	1.167	1.133	0.986	1.169	1.167
11243	1.625	1.332	1.290	1.125	1.896	1.554	1.506	1.313
11301	1.625	1.433	1.299	1.371	1.422	1.254	1.136	1.200
11302	1.200	1.259	1.423	1.257	1.440	1.511	1.708	1.509
11303	1.273	1.385	-	-	1.273	1.385	-	-
1130SX	1.222	1.429	1.455	1.494	0.917	1.071	1.091	1.121
1130DX	1.031	1.385	-	-	1.375	1.846	-	-
Average	1.264	1.304	1.247	1.236	1.328	1.351	1.299	1.246
Stddev	0.241	0.141	0.197	0.178	0.288	0.282	0.249	0.144

Table 4.47 Crack Widths in the Constant Moment Region Outside the Splice
Type B Specimens, P = 6 k

Specimen	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
U11241	0.0110	0.0110	0.0130	0.0140	0.0055	0.0055	0.0065	0.0070
E11241	0.0110	0.0120	0.0130	0.0130	0.0055	0.0060	0.0065	0.0065
U11242	0.0250	0.0270	0.0339	0.0320	0.0063	0.0068	0.0085	0.0080
E11242	0.0180	0.0200	0.0220	0.0230	0.0090	0.0100	0.0110	0.0115
U11243	0.0100	0.0120	0.0140	0.0150	0.0050	0.0060	0.0070	0.0075
E11243	0.0200	0.0220	0.0260	0.0260	0.0100	0.0110	0.0130	0.0130
U11301	0.0100	0.0110	0.0120	0.0130	0.0050	0.0055	0.0060	0.0065
E11301	0.0170	0.0190	0.0210	0.0210	0.0085	0.0095	0.0105	0.0105
U11302	0.0080	0.0080	0.0080	0.0100	0.0080	0.0080	0.0080	0.0100
E11302	0.0080	0.0080	0.0080	0.0080	0.0080	0.0080	0.0080	0.0080
U11303	0.0150	0.0180	0.0200	0.0240	0.0050	0.0060	0.0067	0.0080
E11303	0.0280	0.0320	-	-	0.0070	0.0080	-	-
U1130SX	0.0120	0.0120	0.0130	0.0124	0.0060	0.0060	0.0065	0.0062
E1130SX	0.0680	0.0260	0.0310	0.0340	0.0170	0.0065	0.0078	0.0085
U1130DX	0.0090	0.0080	0.0100	0.0120	0.0045	0.0040	0.0050	0.0060
E1130DX	0.0160	-	-	-	0.0080	-	-	-
Ave Unc	0.0125	0.0134	0.0155	0.0166	0.0057	0.0060	0.0068	0.0074
Stdev Unc	0.0055	0.0063	0.0082	0.0075	0.0011	0.0011	0.0011	0.0013
Ave Epo	0.0233	0.0198	0.0202	0.0208	0.0091	0.0084	0.0095	0.0097
Stdev Epo	0.0190	0.0081	0.0084	0.0093	0.0035	0.0018	0.0024	0.0024
E/U	1.860	1.484	1.303	1.259	1.613	1.411	1.398	1.306

Table 4.48 E/U Ratios of Crack Widths in the Constant Moment Region Outside the Splice
Type B Specimens, $P = 6 \text{ k}$

Specimen Series	Total Crack Width (inches)			Average Crack Width (inches)		
	Cycle Number			Cycle Number		
	2	100000	450000	2	100000	450000
11241	1.000	1.089	1.000	0.929	1.000	1.089
11242	0.720	0.739	0.649	0.719	1.440	1.478
11243	2.000	1.832	1.862	1.733	2.000	1.832
11301	1.700	1.727	1.747	1.615	1.700	1.727
11302	1.000	1.000	1.003	0.800	1.000	1.000
11303	1.867	1.778	-	-	1.400	1.333
1130SX	5.667	2.167	2.385	2.742	2.833	1.083
1130DX	1.778	-	-	-	1.778	-
Average	1.966	1.476	1.441	1.423	1.644	1.363
Stdev	1.569	0.529	0.660	0.775	0.597	0.330
					1.351	0.372
						0.374

Table 4.49 Crack Widths Inside the Splice
Type B Specimens, $P = 6$ k

Specimen	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	10000	45000	100000	2	10000	45000	100000
U11241	0.0180	0.0200	0.0235	0.0240	0.0036	0.0040	0.0059	0.0060
E11241	0.0180	0.0200	0.0255	0.0280	0.0045	0.0050	0.0064	0.0070
U11242	0.0050	0.0060	0.0100	0.0100	0.0050	0.0060	0.0033	0.0033
E11242	0.0160	0.0189	0.0220	0.0260	0.0053	0.0048	0.0055	0.0052
U11243	0.0140	0.0210	0.0279	0.0330	0.0028	0.0042	0.0056	0.0066
E11243	0.0190	0.0220	0.0280	0.0280	0.0048	0.0055	0.0070	0.0070
U11301	0.0140	0.0190	0.0230	0.0220	0.0028	0.0038	0.0046	0.0044
E11301	0.0220	0.0240	0.0245	0.0270	0.0037	0.0040	0.0041	0.0045
U11302	0.0170	0.0190	0.0229	0.0250	0.0034	0.0038	0.0046	0.0050
E11302	0.0220	0.0260	0.0359	0.0360	0.0055	0.0065	0.0090	0.0090
U11303	0.0180	0.0210	0.0269	0.0300	0.0045	0.0053	0.0067	0.0075
E11303	0.0140	0.0220	-	-	0.0047	0.0073	-	-
U1130SX	0.0150	0.0160	0.0200	0.0224	0.0038	0.0040	0.0050	0.0056
E1130SX	0.0100	0.0140	0.0170	0.0180	0.0025	0.0035	0.0043	0.0045
U1130DX	0.0230	0.0310	0.0350	0.0380	0.0038	0.0052	0.0058	0.0063
E1130DX	0.0380	-	-	-	0.0095	-	-	-
Ave Unc	0.0155	0.0191	0.0236	0.0256	0.0037	0.0045	0.0052	0.0056
Stdev Unc	0.0052	0.0069	0.0071	0.0084	0.0008	0.0008	0.0010	0.0013
Ave Epo	0.0199	0.0210	0.0255	0.0272	0.0051	0.0052	0.0060	0.0062
Stdev Epo	0.0084	0.0039	0.0063	0.0057	0.0020	0.0013	0.0018	0.0018
E/U	1.282	1.097	1.078	1.063	1.362	1.154	1.162	1.108

Table 4.50 E/U Ratios of Crack Widths Inside the Splice
Type B Specimens, P = 6 k

Specimen Series	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
11241	1.000	0.998	1.085	1.167	1.250	1.247	1.085	1.167
11242	3.200	3.155	2.200	2.600	1.067	0.794	1.650	1.560
11243	1.357	1.046	1.004	0.848	1.696	1.308	1.255	1.061
11301	1.571	1.263	1.065	1.227	1.310	1.053	0.887	1.023
11302	1.294	1.368	1.571	1.440	1.618	1.711	1.963	1.800
11303	0.778	1.048	-	-	1.037	1.397	-	-
1130SX	0.667	0.875	0.850	0.804	0.667	0.875	0.850	0.804
1130DX	1.652	-	-	-	2.478	-	-	-
Average	1.440	1.393	1.296	1.348	1.390	1.198	1.282	1.236
Stdev	0.794	0.794	0.505	0.659	0.549	0.318	0.443	0.372

Table 4.51 Crack Widths in Constant Moment Region
Type B Specimens, P = 16 k

Specimen	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	10000	45000	100000	2	10000	45000	100000
U11241	0.0530	0.0610	0.0680	0.0710	0.0076	0.0087	0.0097	0.0101
E11241	0.0570	0.0609	0.0645	0.0660	0.0095	0.0102	0.0108	0.0110
U11242	0.0620	0.0640	0.0759	0.0810	0.0124	0.0128	0.0108	0.0116
E11242	0.0720	0.0730	0.0799	0.0840	0.0120	0.0122	0.0133	0.0120
U11243	0.0580	0.0670	0.0749	0.0780	0.0083	0.0096	0.0107	0.0111
E11243	0.0720	0.0799	0.0860	0.0910	0.0120	0.0133	0.0143	0.0152
U11301	0.0450	0.0550	0.0620	0.0650	0.0064	0.0079	0.0089	0.0093
E11301	0.0745	0.0750	0.0820	0.0840	0.0093	0.0094	0.0102	0.0105
U11302	0.0440	0.0480	0.0556	0.0590	0.0073	0.0080	0.0093	0.0098
E11302	0.0540	0.0620	0.0660	0.0730	0.0108	0.0124	0.0132	0.0146
U11303	0.0670	0.0720	0.0818	0.0840	0.0096	0.0103	0.0117	0.0120
E11303	0.0780	0.0900	-	-	0.0111	0.0129	-	-
U1130SX	0.0500	0.0530	0.0570	0.0597	0.0083	0.0088	0.0095	0.0100
E1130SX	0.0660	0.0740	0.0850	0.0900	0.0083	0.0093	0.0106	0.0113
U1130DX	0.0610	0.0680	0.0730	0.0790	0.0076	0.0085	0.0091	0.0099
E1130DX	0.0980	-	-	-	0.0163	-	-	-
Ave Unc	0.0550	0.0610	0.0685	0.0721	0.0084	0.0093	0.0100	0.0105
Stdev Unc	0.0083	0.0083	0.0095	0.0099	0.0018	0.0016	0.0010	0.0010
Ave Epo	0.0714	0.0735	0.0772	0.0813	0.0112	0.0114	0.0121	0.0124
Stdev Epo	0.0136	0.0101	0.0096	0.0099	0.0025	0.0017	0.0017	0.0020
E/U	1.299	1.206	1.127	1.128	1.323	1.219	1.213	1.186

Table 4.52 E/U Ratios of Crack Widths in Constant Moment Region
Type B Specimens, P = 16 k

Specimen Series	Total Crack Width (inches)			Average Crack Width (inches)		
	Cycle Number			Cycle Number		
	2	100000	450000	2	100000	450000
11241	1.075	0.998	0.949	0.930	1.255	1.165
11242	1.161	1.140	1.053	1.037	0.968	0.950
11243	1.241	1.193	1.148	1.167	1.448	1.392
11301	1.656	1.364	1.322	1.292	1.449	1.193
11302	1.227	1.292	1.186	1.237	1.473	1.550
11303	1.164	1.250	-	-	1.164	1.250
1130SX	1.320	1.396	1.491	1.508	0.990	1.047
1130DX	1.607	-	-	-	2.142	-
Average	1.306	1.233	1.192	1.195	1.361	1.221
Stdev	0.213	0.137	0.194	0.203	0.374	0.202
						0.129
						0.177

Table 4.53 Crack Widths in the Constant Moment Region Outside the Splice
Type B Specimens, P = 16 k

Specimen	Total				Average			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
U11241	0.0210	0.0210	0.0240	0.0240	0.0105	0.0105	0.0120	0.0120
E11241	0.0220	0.0220	0.0223	0.0210	0.0110	0.0110	0.0111	0.0105
U11242	0.0530	0.0540	0.0570	0.0590	0.0133	0.0135	0.0142	0.0148
E11242	0.0360	0.0350	0.0380	0.0350	0.0180	0.0175	0.0190	0.0175
U11243	0.0240	0.0240	0.0250	0.0260	0.0120	0.0120	0.0125	0.0130
E11243	0.0360	0.0370	0.0410	0.0420	0.0180	0.0185	0.0205	0.0210
U11301	0.0180	0.0200	0.0230	0.0230	0.0090	0.0100	0.0115	0.0115
E11301	0.0350	0.0340	0.0380	0.0360	0.0175	0.0170	0.0190	0.0180
U11302	0.0140	0.0140	0.0150	0.0160	0.0140	0.0140	0.0150	0.0160
E11302	0.0140	0.0150	0.0150	0.0150	0.0140	0.0150	0.0150	0.0150
U11303	0.0320	0.0330	0.0370	0.0380	0.0107	0.0110	0.0123	0.0127
E11303	0.0540	0.0580	-	-	0.0135	0.0145	-	-
U1130SX	0.0210	0.0220	0.0230	0.0247	0.0105	0.0110	0.0115	0.0124
E1130SX	0.0430	0.0500	0.0570	0.0610	0.0108	0.0125	0.0143	0.0153
U1130DX	0.0150	0.0170	0.0170	0.0190	0.0075	0.0085	0.0085	0.0095
E1130DX	0.0360	-	-	-	0.0180	-	-	-
Ave Unc	0.0248	0.0256	0.0276	0.0287	0.0109	0.0113	0.0122	0.0127
Stdev Unc	0.0127	0.0127	0.0135	0.0138	0.0021	0.0018	0.0020	0.0020
Ave Epo	0.0345	0.0359	0.0352	0.0350	0.0151	0.0151	0.0165	0.0162
Stdev Epo	0.0122	0.0148	0.0148	0.0163	0.0032	0.0027	0.0036	0.0035
E/U	1.394	1.399	1.275	1.219	1.381	1.339	1.351	1.274

Table 4.54 E/U Ratios of Crack Widths in the Constant Moment Region Outside the Splice
Type B Specimens, P = 16 k

Specimen Series	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
11241	1.048	1.048	0.927	0.875	1.048	1.048	0.927	0.875
11242	0.679	0.649	0.666	0.593	1.358	1.297	1.333	1.186
11243	1.500	1.541	1.640	1.615	1.500	1.541	1.640	1.615
11301	1.944	1.700	1.652	1.565	1.944	1.700	1.652	1.565
11302	1.000	1.071	1.000	0.938	1.000	1.071	1.000	0.938
11303	1.688	1.758	-	-	1.266	1.318	-	-
1130SX	2.048	2.273	2.478	2.470	1.024	1.136	1.239	1.235
1130DX	2.400	-	-	-	2.400	-	-	-
Average	1.538	1.434	1.394	1.343	1.442	1.302	1.298	1.236
stdev	0.593	0.546	0.664	0.684	0.498	0.245	0.308	0.308

Table 4.55 Crack Widths Inside the Splice
Type B Specimens, P = 16 k

Specimen	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	10000	45000	100000	2	10000	45000	100000
U11241	0.0320	0.0400	0.0410	0.0430	0.0064	0.0080	0.0103	0.0108
E11241	0.0350	0.0389	0.0423	0.0450	0.0088	0.0097	0.0106	0.0113
U11242	0.0090	0.0100	0.0190	0.0220	0.0090	0.0100	0.0063	0.0073
E11242	0.0360	0.0380	0.0420	0.0490	0.0090	0.0095	0.0105	0.0098
U11243	0.0340	0.0430	0.0499	0.0520	0.0068	0.0086	0.0100	0.0104
E11243	0.0360	0.0429	0.0450	0.0490	0.0090	0.0107	0.0113	0.0123
U11301	0.0270	0.0350	0.0390	0.0400	0.0054	0.0070	0.0078	0.0080
E11301	0.0395	0.0410	0.0440	0.0480	0.0066	0.0068	0.0073	0.0080
U11302	0.0300	0.0340	0.0406	0.0430	0.0060	0.0068	0.0081	0.0086
E11302	0.0400	0.0470	0.0510	0.0580	0.0100	0.0118	0.0127	0.0145
U11303	0.0350	0.0390	0.0448	0.0460	0.0088	0.0098	0.0112	0.0115
E11303	0.0240	0.0320	-	-	0.0080	0.0107	-	-
U1130SX	0.0290	0.0310	0.0340	0.0350	0.0073	0.0078	0.0085	0.0088
E1130SX	0.0230	0.0240	0.0280	0.0290	0.0058	0.0060	0.0070	0.0073
U1130DX	0.0460	0.0510	0.0560	0.0600	0.0077	0.0085	0.0093	0.0100
E1130DX	0.0620	-	-	-	0.0155	-	-	-
Ave Unc	0.0303	0.0354	0.0405	0.0426	0.0072	0.0083	0.0089	0.0094
Stdev Unc	0.0104	0.0120	0.0111	0.0113	0.0013	0.0012	0.0016	0.0015
Ave Epo	0.0369	0.0377	0.0420	0.0463	0.0091	0.0093	0.0099	0.0105
Stdev Epo	0.0120	0.0076	0.0076	0.0095	0.0029	0.0021	0.0023	0.0027
E/U	1.221	1.065	1.037	1.087	1.267	1.122	1.107	1.116

Table 4.56 E/U Ratios of Crack Widths Inside the Splice
Type B Specimens, P = 16 k

Specimen Series	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
11241	1.094	0.973	1.030	1.047	1.367	1.216	1.030	1.047
11242	4.000	3.795	2.212	2.227	1.000	0.949	1.659	1.336
11243	1.059	0.998	0.902	0.942	1.324	1.248	1.128	1.178
11301	1.463	1.171	1.128	1.200	1.219	0.976	0.940	1.000
11302	1.333	1.382	1.255	1.349	1.667	1.728	1.569	1.686
11303	0.686	0.821	-	-	0.914	1.094	-	-
1130SX	0.793	0.774	0.824	0.829	0.793	0.774	0.824	0.829
1130DX	1.348	-	-	-	2.022	-	-	-
Average	1.472	1.416	1.225	1.266	1.288	1.141	1.192	1.179
Stdev	1.057	1.069	0.508	0.506	0.407	0.306	0.344	0.301

Table 4.57 Crack Widths in Constant Moment Region
Type B Specimens, P = Peak Repeating Load

Specimen	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
U11241	0.0530	0.0610	0.0680	0.0710	0.0076	0.0087	0.0097	0.0101
E11241	0.0570	0.0609	0.0645	0.0660	0.0095	0.0102	0.0108	0.0110
U11242	0.0620	0.0640	0.0788	0.0810	0.0124	0.0128	0.0113	0.0116
E11242	0.0720	0.0730	0.0799	0.0840	0.0120	0.0122	0.0133	0.0120
U11243	0.0580	0.0670	0.0749	0.0780	0.0083	0.0096	0.0107	0.0111
E11243	0.0720	0.0799	0.0860	0.0910	0.0120	0.0133	0.0143	0.0152
U11301	0.0690	0.0700	0.0770	0.0790	0.0099	0.0100	0.0110	0.0113
E11301	0.0880	0.0930	0.0995	0.1040	0.0110	0.0116	0.0124	0.0130
U11302	0.0550	0.0600	0.0699	0.0740	0.0092	0.0100	0.0116	0.0123
E11302	0.0670	0.0770	0.0820	0.0830	0.0134	0.0154	0.0164	0.0166
U11303	0.0900	0.0970	0.0998	0.1010	0.0129	0.0139	0.0143	0.0144
E11303	0.1000	0.1120	-	-	0.0143	0.0160	-	-
U1130SX	0.0680	0.0720	0.0710	0.0709	0.0113	0.0120	0.0118	0.0118
E1130SX	0.0880	0.0940	0.0990	0.1290	0.0110	0.0118	0.0124	0.0161
U1130DX	0.0770	0.0850	0.0880	0.0950	0.0096	0.0106	0.0110	0.0119
E1130DX	0.1180	-	-	-	0.0197	-	-	-
Ave Unc	0.0665	0.0720	0.0784	0.0812	0.0101	0.0109	0.0114	0.0118
Stdev Unc	0.0124	0.0128	0.0107	0.0111	0.0019	0.0018	0.0013	0.0012
Ave Epo	0.0828	0.0843	0.0851	0.0928	0.0129	0.0129	0.0133	0.0140
Stdev Epo	0.0198	0.0168	0.0131	0.0216	0.0031	0.0021	0.0019	0.0023
E/U	1.244	1.170	1.086	1.143	1.268	1.180	1.161	1.182

Table 4.58 E/U Ratios of Crack Widths in Constant Moment Region
Type B Specimens, P = Peak Repeating Load

Specimen Series	Total Crack Width (inches)			Average Crack Width (inches)		
	Cycle Number			Cycle Number		
	2	100000	450000	2	100000	450000
11241	1.075	0.998	0.949	0.930	1.255	1.165
11242	1.161	1.140	1.014	1.037	0.968	0.950
11243	1.241	1.193	1.148	1.167	1.448	1.392
11301	1.275	1.329	1.292	1.316	1.116	1.163
11302	1.218	1.283	1.173	1.122	1.462	1.540
11303	1.111	1.155	-	-	1.111	1.155
1130SX	1.294	1.306	1.394	1.819	0.971	0.979
1130DX	1.532	-	-	-	2.043	-
Average	1.239	1.201	1.162	1.232	1.297	1.192
Stdev	0.141	0.116	0.167	0.316	0.357	0.211
						0.142
						0.150

Table 4.59 Crack Widths in the Constant Moment Region Outside the Splice
Type B Specimens, P = Peak Repeating Load

Specimen	Total Crack Width (inches)			Average Crack Width (inches)		
	Cycle Number			Cycle Number		
	2	10000	450000	2	10000	450000
U11241	0.0210	0.0210	0.0240	0.0240	0.0105	0.0105
E11241	0.0220	0.0220	0.0223	0.0210	0.0110	0.0111
U11242	0.0530	0.0540	0.0599	0.0590	0.0133	0.0135
E11242	0.0360	0.0350	0.0380	0.0350	0.0180	0.0175
U11243	0.0240	0.0240	0.0250	0.0260	0.0120	0.0125
E11243	0.0360	0.0370	0.0410	0.0420	0.0180	0.0205
U11301	0.0260	0.0270	0.0290	0.0300	0.0130	0.0135
E11301	0.0400	0.0400	0.0440	0.0450	0.0200	0.0220
U11302	0.0140	0.0170	0.0180	0.0190	0.0140	0.0170
E11302	0.0160	0.0170	0.0170	0.0180	0.0160	0.0170
U11303	0.0430	0.0450	0.0469	0.0450	0.0143	0.0150
E11303	0.0680	0.0740	-	-	0.0170	0.0185
U1130SX	0.0290	0.0310	0.0290	0.0280	0.0145	0.0155
E1130SX	0.0600	0.0620	0.0660	0.0710	0.0150	0.0155
U1130DX	0.0210	0.0220	0.0230	0.0230	0.0105	0.0110
E1130DX	0.0460	-	-	-	0.0230	-
Ave Unc	0.0289	0.0301	0.0318	0.0318	0.0128	0.0135
Stdev Unc	0.0129	0.0129	0.0142	0.0135	0.0016	0.0023
Ave Epo	0.0405	0.0410	0.0380	0.0387	0.0173	0.0169
Stdev Epo	0.0175	0.0205	0.0174	0.0192	0.0035	0.0029
E/U	1.403	1.361	1.194	1.218	1.352	1.249
					1.245	1.252

Table 4.60 E/U Ratios of Crack Widths in the Constant Moment Region Outside the Splice
Type B Specimens, P = 16 k

Specimen Series	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
11241	1.048	1.048	0.927	0.875	1.048	1.048	0.927	0.875
11242	0.679	0.649	0.634	0.593	1.358	1.297	1.268	1.186
11243	1.500	1.541	1.640	1.615	1.500	1.541	1.640	1.615
11301	1.538	1.481	1.517	1.500	1.538	1.481	1.517	1.500
11302	1.143	1.000	0.944	0.947	1.143	1.000	0.944	0.947
11303	1.581	1.644	-	-	1.186	1.233	-	-
1130SX	2.069	2.000	2.276	2.536	1.034	1.000	1.138	1.268
1130DX	2.190	-	-	-	2.190	-	-	-
Average	1.469	1.338	1.323	1.344	1.375	1.229	1.239	1.232
Stdev	0.508	0.460	0.603	0.701	0.382	0.225	0.294	0.293

Table 4.61 Crack Widths Inside the Splice
Type B Specimens, P = Peak Repeating Load

Specimen	Total Crack Width (inches)			Average Crack Width (inches)		
	Cycle Number			Cycle Number		
	2	10000	450000	2	10000	450000
U11241	0.0320	0.0400	0.0410	0.0430	0.0064	0.0080
E11241	0.0350	0.0389	0.0423	0.0450	0.0088	0.0097
U11242	0.0090	0.0100	0.0190	0.0220	0.0090	0.0100
E11242	0.0360	0.0380	0.0420	0.0490	0.0090	0.0095
U11243	0.0340	0.0430	0.0499	0.0520	0.0068	0.0086
E11243	0.0360	0.0429	0.0450	0.0490	0.0090	0.0107
U11301	0.0430	0.0430	0.0480	0.0490	0.0086	0.0086
E11301	0.0480	0.0530	0.0555	0.0590	0.0080	0.0088
U11302	0.0410	0.0430	0.0519	0.0550	0.0082	0.0086
E11302	0.0510	0.0600	0.0650	0.0650	0.0128	0.0150
U11303	0.0470	0.0520	0.0529	0.0560	0.0118	0.0130
E11303	0.0320	0.0380	-	-	0.0107	0.0127
U1130SX	0.0390	0.0410	0.0420	0.0429	0.0098	0.0103
E1130SX	0.0280	0.0320	0.0330	0.0360	0.0070	0.0080
U1130DX	0.0560	0.0630	0.0650	0.0720	0.0093	0.0105
E1130DX	0.0720	-	-	-	0.0180	-
Ave Unc	0.0376	0.0419	0.0462	0.0490	0.0087	0.0097
Stdev Unc	0.0138	0.0150	0.0133	0.0143	0.0017	0.0016
Ave Epo	0.0423	0.0433	0.0471	0.0505	0.0104	0.0106
Stdev Epo	0.0143	0.0098	0.0113	0.0103	0.0035	0.0024
E/U	1.123	1.033	1.020	1.031	1.191	1.097

Table 4.62 E/U Ratios of Crack Widths Inside the Splice
Type B Specimens, P = Peak Repeating Load

Specimen Series	Total Crack Width (inches)				Average Crack Width (inches)			
	Cycle Number				Cycle Number			
	2	100000	450000	1000000	2	100000	450000	1000000
11241	1.094	0.973	1.030	1.047	1.367	1.216	1.030	1.047
11242	4.000	3.795	2.212	2.227	1.000	0.949	1.659	1.336
11243	1.059	0.998	0.902	0.942	1.324	1.248	1.128	1.178
11301	1.116	1.233	1.156	1.204	0.930	1.027	0.964	1.003
11302	1.244	1.395	1.252	1.182	1.555	1.744	1.566	1.477
11303	0.681	0.731	-	-	0.908	0.974	-	-
1130SX	0.718	0.780	0.786	0.839	0.718	0.780	0.786	0.839
1130DX	1.286	-	-	-	1.929	-	-	-
Average	1.400	1.415	1.223	1.240	1.216	1.134	1.189	1.147
Stdev	1.074	1.075	0.513	0.503	0.401	0.313	0.348	0.233

Table 4.63 Summary of Statistics of Crack Widths in the Constant Moment Region
Type A Specimens

Load	Average and Std. Deviation	Total Crack Width (inches)				Average Crack Width (inches)			
		Cycle Number				Cycle Number			
		2	100000	450000	1000000	2	100000	450000	1000000
P = 2 k	Ave Unc	0.066	0.075	0.083	0.089	0.011	0.012	0.013	0.014
	Stdev Unc	0.014	0.015	0.015	0.015	0.003	0.003	0.003	0.003
	Ave Epo	0.070	0.077	0.088	0.096	0.013	0.015	0.017	0.017
	Stdev Epo	0.018	0.021	0.021	0.028	0.003	0.004	0.004	0.005
	E/U	1.056	1.026	1.061	1.073	1.217	1.190	1.234	1.161
P = 3.5 k	Ave Unc	0.092	0.127	0.141	0.147	0.015	0.021	0.023	0.024
	Stdev Unc	0.016	0.083	0.097	0.097	0.003	0.014	0.017	0.017
	Ave Epo	0.099	0.102	0.114	0.122	0.019	0.019	0.021	0.021
	Stdev Epo	0.021	0.024	0.026	0.032	0.003	0.004	0.005	0.005
	E/U	1.079	0.805	0.806	0.833	1.248	0.928	0.932	0.896
P = Peak Rep. Load	Ave Unc	0.116	0.121	0.131	0.137	0.019	0.020	0.021	0.022
	Stdev Unc	0.030	0.031	0.030	0.032	0.006	0.006	0.006	0.006
	Ave Epo	0.123	0.126	0.137	0.145	0.023	0.024	0.026	0.025
	Stdev Epo	0.037	0.038	0.041	0.051	0.006	0.007	0.007	0.008
	E/U	1.054	1.040	1.047	1.059	1.209	1.198	1.212	1.131
Average of	Uncoated	0.091	0.108	0.118	0.124	0.015	0.018	0.019	0.020
	Stdev Unc.	0.020	0.043	0.048	0.048	0.004	0.008	0.009	0.009
	Epoxy-Coated	0.097	0.102	0.113	0.121	0.018	0.019	0.021	0.021
	Stdev Epo E/U	0.025 1.063	0.028 0.957	0.029 0.971	0.037 0.988	0.004 1.225	0.005 1.105	0.005 1.126	0.006 1.063

Table 4.64 Summary of E/U Ratios of Crack Widths in the Constant Moment Region
Type A Specimens

Load	E/U Ratios	Total Crack Width (inches)				Average Crack Width (inches)			
		Cycle Number				Cycle Number			
		2	100000	450000	1000000	2	100000	450000	1000000
P = 2 k	Average	1.075	1.025	1.064	1.096	1.246	1.200	1.247	1.222
	Std. Dev	0.267	0.161	0.176	0.195	0.206	0.150	0.174	0.212
P = 3.5 k	Average	1.092	0.936	0.949	0.962	1.271	1.108	1.125	1.087
	Std. Dev	0.228	0.308	0.311	0.364	0.184	0.346	0.357	0.422
P = Peak Rep. Load	Average	1.073	1.052	1.048	1.120	1.244	1.222	1.223	1.245
	Std. Dev	0.149	0.051	0.003	0.218	0.130	0.018	0.044	0.208
Average E/U Ave. Std. Dev	Average E/U	1.080	1.004	1.020	1.059	1.254	1.176	1.199	1.184
	Ave. Std. Dev	0.215	0.173	0.163	0.259	0.173	0.171	0.192	0.281

Table 4.65 Summary of Statistics of Crack Widths in the Constant Moment Region Outside the Splice
Type A Specimens

Load	Average and Std. Deviation	Total Crack Width (inches)				Average Crack Width (inches)			
		Cycle Number				Cycle Number			
		2	100000	450000	1000000	2	100000	450000	1000000
P = 2 k	Ave Unc	0.047	0.053	0.057	0.061	0.012	0.014	0.015	0.015
	Stdv Unc	0.014	0.015	0.016	0.017	0.003	0.003	0.003	0.003
	Ave Epo	0.052	0.056	0.062	0.072	0.015	0.016	0.017	0.018
	Stdv Epo	0.015	0.016	0.017	0.018	0.003	0.004	0.004	0.005
	E/U	1.122	1.056	1.081	1.186	1.218	1.150	1.166	1.186
P = 3.5 k	Ave Unc	0.064	0.096	0.103	0.111	0.016	0.024	0.026	0.036
	Stdv Unc	0.018	0.080	0.098	0.095	0.004	0.020	0.024	0.028
	Ave Epo	0.074	0.074	0.081	0.092	0.020	0.020	0.022	0.023
	Stdv Epo	0.019	0.020	0.022	0.021	0.004	0.004	0.004	0.006
	E/U	1.155	0.771	0.786	0.824	1.241	0.836	0.835	0.652
P = Peak Rep. Load	Ave Unc	0.081	0.085	0.086	0.094	0.021	0.021	0.022	0.032
	Stdv Unc	0.027	0.028	0.035	0.030	0.006	0.006	0.007	0.018
	Ave Epo	0.091	0.092	0.098	0.109	0.025	0.025	0.027	0.028
	Stdv Epo	0.031	0.031	0.033	0.036	0.007	0.007	0.007	0.009
	E/U	1.114	1.084	1.146	1.152	1.200	1.176	1.212	0.873
Average of	Uncoated	0.064	0.078	0.082	0.089	0.016	0.020	0.021	0.028
	Stdv Unc.	0.019	0.041	0.050	0.047	0.004	0.010	0.011	0.016
	Epoxy-Coated	0.072	0.074	0.080	0.091	0.020	0.020	0.022	0.023
	Stdv Epo	0.022	0.022	0.024	0.025	0.005	0.005	0.005	0.007
	E/U	1.131	0.970	1.004	1.054	1.220	1.054	1.071	0.904

Table 4.66 Summary of E/U Ratios of Crack Widths in the Constant Moment Region Outside the Splice
Type A Specimens

Load	E/U Ratios	Total Crack Width (inches)				Average Crack Width (inches)			
		Cycle Number				Cycle Number			
		2	100000	450000	1000000	2	100000	450000	1000000
P = 2 k	Average	1.238	1.135	1.174	1.301	1.250	1.164	1.184	1.210
	Std. Dev	0.567	0.424	0.489	0.440	0.280	0.156	0.189	0.226
P = 3.5 k	Average	1.270	1.059	1.174	1.138	1.267	1.070	1.144	0.841
	Std. Dev	0.582	0.595	0.638	0.641	0.212	0.384	0.491	0.510
P = Peak Rep. Load	Average	1.250	1.196	1.300	1.315	1.238	1.203	1.270	1.018
	Std. Dev	0.603	0.509	0.515	0.455	0.241	0.210	0.328	0.434
Average E/U Ave. Std. Dev	Average E/U	1.252	1.130	1.216	1.251	1.252	1.146	1.199	1.023
	Ave. Std. Dev	0.584	0.509	0.548	0.512	0.244	0.250	0.336	0.390

Table 4.67 Summary Statistics of Crack Widths Inside the Splice
Type A Specimens

Load	Average and Std. Deviation	Total Crack Width (inches)				Average Crack Width (inches)			
		Cycle Number				Cycle Number			
		2	100000	450000	1000000	2	100000	450000	1000000
P = 2 k	Ave Unc	0.020	0.022	0.026	0.029	0.009	0.010	0.011	0.013
	Stddev Unc	0.005	0.006	0.008	0.009	0.003	0.004	0.004	0.004
	Ave Epo	0.018	0.021	0.026	0.024	0.010	0.013	0.016	0.013
	Stddev Epo	0.008	0.010	0.013	0.013	0.005	0.006	0.008	0.006
	E/U	0.898	0.956	1.017	0.835	1.177	1.291	1.364	1.065
P = 3.5 k	Ave Unc	0.027	0.031	0.034	0.036	0.012	0.014	0.015	0.016
	Stddev Unc	0.008	0.010	0.011	0.011	0.003	0.005	0.005	0.005
	Ave Epo	0.025	0.028	0.033	0.031	0.015	0.017	0.020	0.017
	Stddev Epo	0.009	0.012	0.015	0.014	0.005	0.007	0.009	0.006
	E/U	0.901	0.912	0.974	0.862	1.226	1.237	1.333	1.100
P = Peak Rep. Load	Ave Unc	0.035	0.037	0.041	0.043	0.014	0.015	0.018	0.019
	Stddev Unc	0.010	0.011	0.013	0.013	0.006	0.007	0.007	0.007
	Ave Epo	0.032	0.034	0.039	0.036	0.019	0.020	0.023	0.020
	Stddev Epo	0.014	0.015	0.019	0.018	0.008	0.009	0.011	0.007
	E/U	0.914	0.936	0.958	0.851	1.345	1.383	1.265	1.045
Average of	Uncoated	0.027	0.030	0.034	0.036	0.012	0.013	0.015	0.016
	Stddev Unc.	0.008	0.009	0.011	0.011	0.004	0.005	0.005	0.005
	Epoxy-Coated	0.025	0.028	0.033	0.030	0.015	0.017	0.019	0.017
	Stddev Epo	0.010	0.012	0.016	0.015	0.006	0.008	0.009	0.006
	E/U	0.904	0.935	0.983	0.849	1.249	1.303	1.321	1.070

Table 4.68 Summary of E/U Ratios of Crack Widths Inside the Splice
Type A Specimens

Load	E/U Ratios	Total Crack Width (inches)				Average Crack Width (inches)			
		Cycle Number				Cycle Number			
		2	100000	450000	1000000	2	100000	450000	1000000
P = 2 k	Average	0.906	0.976	1.036	0.947	1.155	1.255	1.320	1.202
	Std. Dev	0.309	0.362	0.391	0.394	0.318	0.283	0.282	0.261
P = 3.5 k	Average	0.953	0.954	1.026	0.983	1.223	1.222	1.299	1.238
	Std. Dev	0.344	0.350	0.402	0.430	0.319	0.281	0.303	0.244
P = Peak	Average	0.938	0.954	0.978	0.990	1.433	1.470	1.235	1.245
	Std. Dev	0.369	0.364	0.386	0.440	0.662	0.694	0.269	0.252
Rep. Load	Average E/U	0.932	0.961	1.013	0.973	1.271	1.315	1.284	1.228
	Ave. Std. Dev	0.341	0.359	0.393	0.421	0.433	0.419	0.285	0.252

Table 4.69 Summary of Crack Widths in the Constant Moment Region
Type B Specimens

Load	Average and Std. Deviation	Total Crack Width (inches)				Average Crack Width (inches)			
		Cycle Number				Cycle Number			
		2	100000	450000	1000000	2	100000	450000	1000000
P = 6 k	Ave Unc	0.028	0.033	0.039	0.042	0.004	0.005	0.006	0.006
	Stddev Unc	0.004	0.005	0.006	0.007	0.001	0.001	0.001	0.001
	Ave Epo	0.035	0.042	0.046	0.048	0.006	0.007	0.007	0.007
	Stddev Epo	0.005	0.008	0.005	0.005	0.001	0.001	0.001	0.001
	E/U	1.246	1.307	1.161	1.130	1.298	1.338	1.263	1.193
P = 16 k	Ave Unc	0.055	0.061	0.069	0.072	0.008	0.009	0.010	0.010
	Stddev Unc	0.008	0.008	0.010	0.010	0.002	0.002	0.001	0.001
	Ave Epo	0.071	0.074	0.077	0.081	0.011	0.011	0.012	0.012
	Stddev Epo	0.014	0.010	0.010	0.010	0.002	0.002	0.002	0.002
	E/U	1.299	1.206	1.127	1.128	1.323	1.219	1.213	1.186
P = Peak Rep. Load	Ave Unc	0.067	0.072	0.078	0.081	0.010	0.011	0.011	0.012
	Stddev Unc	0.012	0.013	0.011	0.011	0.002	0.002	0.001	0.001
	Ave Epo	0.083	0.084	0.085	0.093	0.013	0.013	0.013	0.014
	Stddev Epo	0.020	0.017	0.013	0.022	0.003	0.002	0.002	0.002
	E/U	1.244	1.170	1.086	1.143	1.268	1.180	1.161	1.182
Average of	Uncoated	0.050	0.055	0.062	0.065	0.008	0.008	0.009	0.009
	Stddev Unc.	0.008	0.009	0.009	0.009	0.002	0.001	0.001	0.001
	Epoxy-Coated	0.063	0.067	0.069	0.074	0.010	0.010	0.011	0.011
	Stddev Epo	0.013	0.012	0.009	0.012	0.002	0.002	0.002	0.002
	E/U	1.263	1.228	1.125	1.134	1.296	1.246	1.212	1.187

Table 4.70 Summary of E/U Ratios of Crack Widths in the Constant Moment Region
Type B Specimens

Load	E/U Ratios	Total Crack Width (inches)				Average Crack Width (inches)			
		Cycle Number				Cycle Number			
		2	100000	450000	1000000	2	100000	450000	1000000
P = 6 k	Average	1.264	1.304	1.247	1.236	1.328	1.351	1.299	1.246
	Std. Dev	0.241	0.141	0.197	0.178	0.288	0.282	0.249	0.144
P = 16 k	Average	1.306	1.233	1.192	1.195	1.361	1.221	1.229	1.205
	Std. Dev	0.213	0.137	0.194	0.203	0.374	0.202	0.129	0.177
P = Peak Rep. Load	Average	1.239	1.201	1.162	1.232	1.297	1.190	1.202	1.224
	Std. Dev	0.141	0.116	0.167	0.316	0.357	0.212	0.142	0.150
Average E/U Ave. Std. Dev	Average E/U	1.270	1.246	1.200	1.221	1.328	1.254	1.243	1.225
	Ave. Std. Dev	0.199	0.131	0.186	0.232	0.340	0.232	0.173	0.157

Table 4.71 Summary of Statistics of Crack Widths in the Constant Moment Region Outside the Splice
Type B Specimens

Load	Average and Std. Deviation	Total Crack Width (inches)				Average Crack Width (inches)			
		Cycle Number				Cycle Number			
		2	100000	450000	1000000	2	100000	450000	1000000
P = 6 k	Ave Unc	0.013	0.013	0.015	0.017	0.006	0.006	0.007	0.007
	Stddev Unc	0.005	0.006	0.008	0.008	0.001	0.001	0.001	0.001
	Ave Epo	0.023	0.020	0.020	0.021	0.009	0.008	0.009	0.010
	Stddev Epo	0.019	0.008	0.008	0.009	0.003	0.002	0.002	0.002
	E/U	1.860	1.484	1.303	1.259	1.613	1.411	1.398	1.306
P = 16 k	Ave Unc	0.025	0.026	0.028	0.029	0.011	0.011	0.012	0.013
	Stddev Unc	0.013	0.013	0.014	0.014	0.002	0.002	0.002	0.002
	Ave Epo	0.035	0.036	0.035	0.035	0.015	0.015	0.016	0.016
	Stddev Epo	0.012	0.015	0.015	0.016	0.003	0.003	0.004	0.004
	E/U	1.394	1.399	1.275	1.219	1.381	1.339	1.351	1.274
P = Peak Rep. Load	Ave Unc	0.029	0.030	0.032	0.032	0.013	0.014	0.014	0.014
	Stddev Unc	0.013	0.013	0.014	0.013	0.002	0.002	0.002	0.002
	Ave Epo	0.041	0.041	0.038	0.039	0.017	0.017	0.018	0.018
	Stddev Epo	0.018	0.020	0.017	0.019	0.004	0.003	0.004	0.004
	E/U	1.403	1.361	1.194	1.218	1.352	1.249	1.245	1.252
Average of	Uncoated	0.022	0.023	0.025	0.026	0.010	0.010	0.011	0.011
	Stddev Unc.	0.010	0.011	0.012	0.012	0.002	0.002	0.002	0.002
	Epoxy-Coated	0.033	0.032	0.031	0.032	0.014	0.013	0.015	0.015
	Stddev Epo	0.016	0.014	0.014	0.015	0.003	0.003	0.003	0.003
	E/U	1.552	1.415	1.257	1.232	1.449	1.333	1.332	1.277

Table 4.72 Summary of E/U Ratios of Crack Widths in the Constant Moment Region Outside the Splice
Type B Specimens

Load	E/U Ratios	Total Crack Width (inches)				Average Crack Width (inches)			
		Cycle Number				Cycle Number			
		2	100000	450000	1000000	2	100000	450000	1000000
P = 6 k	Average	1.966	1.476	1.441	1.423	1.644	1.363	1.351	1.314
	Std. Dev	1.569	0.529	0.660	0.775	0.597	0.330	0.372	0.374
P = 16 k	Average	1.538	1.434	1.394	1.343	1.442	1.302	1.298	1.236
	Std. Dev	0.593	0.546	0.664	0.684	0.498	0.245	0.308	0.308
P = Peak Rep. Load	Average	1.469	1.338	1.323	1.344	1.375	1.229	1.239	1.232
	Std. Dev	0.508	0.460	0.603	0.701	0.382	0.225	0.294	0.293
	Average	1.658	1.416	1.386	1.370	1.487	1.298	1.296	1.261
	Std. Dev	0.890	0.511	0.642	0.720	0.492	0.267	0.325	0.325

Table 4.73 Summary of Statistics of Crack Widths Inside the Splice
Type B Specimens

Load	Average and Std. Deviation	Total Crack Width (inches)				Average Crack Width (inches)			
		Cycle Number				Cycle Number			
		2	100000	450000	1000000	2	100000	450000	1000000
P = 6 k	Ave Unc	0.016	0.019	0.024	0.026	0.004	0.005	0.005	0.006
	Stdev Unc	0.005	0.007	0.007	0.008	0.001	0.001	0.001	0.001
	Ave Epo	0.020	0.021	0.025	0.027	0.005	0.005	0.006	0.006
	Stdev Epo	0.008	0.004	0.006	0.006	0.002	0.001	0.002	0.002
	E/U	1.282	1.097	1.078	1.063	1.362	1.154	1.162	1.108
P = 16 k	Ave Unc	0.030	0.035	0.041	0.043	0.007	0.008	0.009	0.009
	Stdev Unc	0.010	0.012	0.011	0.011	0.001	0.001	0.002	0.001
	Ave Epo	0.037	0.038	0.042	0.046	0.009	0.009	0.010	0.011
	Stdev Epo	0.012	0.008	0.008	0.010	0.003	0.002	0.002	0.003
	E/U	1.221	1.065	1.037	1.087	1.267	1.122	1.107	1.116
P = Peak Rep. Load	Ave Unc	0.038	0.042	0.046	0.049	0.009	0.010	0.010	0.011
	Stdev Unc	0.014	0.015	0.013	0.014	0.002	0.002	0.002	0.002
	Ave Epo	0.042	0.043	0.047	0.051	0.010	0.011	0.011	0.011
	Stdev Epo	0.014	0.010	0.011	0.010	0.004	0.002	0.003	0.003
	E/U	1.123	1.033	1.020	1.031	1.191	1.097	1.086	1.060
Average of	Uncoated	0.028	0.032	0.037	0.039	0.007	0.008	0.008	0.009
	Stdev Unc.	0.010	0.011	0.010	0.011	0.001	0.001	0.001	0.002
	Epoxy-Coated	0.033	0.034	0.038	0.041	0.008	0.008	0.009	0.009
	Stdev Epo	0.012	0.007	0.008	0.009	0.003	0.002	0.002	0.002
	E/U	1.209	1.065	1.045	1.060	1.273	1.125	1.119	1.095

Table 4.74 Summary of E/U Ratios of Crack Widths Inside the Splice
Type B Specimens

Load	E/U Ratios	Total Crack Width (inches)				Average Crack Width (inches)			
		Cycle Number				Cycle Number			
		2	100000	450000	1000000	2	100000	450000	1000000
P = 6 k	Average	1.440	1.393	1.296	1.348	1.390	1.198	1.282	1.236
	Std. Dev	0.794	0.794	0.505	0.659	0.549	0.318	0.443	0.372
P = 16 k	Average	1.472	1.416	1.225	1.266	1.288	1.141	1.192	1.179
	Std. Dev	1.057	1.069	0.508	0.506	0.407	0.306	0.344	0.301
P = Peak Rep. Load	Average	1.400	1.415	1.223	1.240	1.216	1.134	1.189	1.147
	Std. Dev	1.074	1.075	0.513	0.503	0.401	0.313	0.348	0.233
	Average	1.437	1.408	1.248	1.284	1.298	1.158	1.221	1.187
	Std. Dev	0.975	0.980	0.509	0.556	0.453	0.312	0.378	0.302

Table 4.75 Mean Stress, Splitting Load, Failure Load, and Post-Splitting Load

Specimen	Peak Stress (ksi)	Stress Range (ksi)	Mean Stress (ksi)	f'c (ksi)	Splitting Load (k)	Average Split-Load (k)	Failure Load (k)	Average Fail Load (k)	Post-Split. Load (k)
Uncoated Specimens									
U7241	24	8.74	19.63	3	5.50	6.25	5.99	6.53	0.28
U7242	24	8.74	19.63	4.7	7.00		7.07		
U7301	30	8.74	25.63	3.0	5.50	5.50	6.75	6.75	1.25
U7363	36	15	28.50	4.0	8.50	8.50	9.00	9.00	0.50
U7361	36	8.74	31.63	5.2	9.20	8.85	9.20	9.00	0.15
U7362	36	8.74	31.63	5.3	8.50		8.80		
U736SX	36	8.74	31.63	5.3	8.40	8.40	8.50	8.50	0.10
Average =					7.42		7.89		0.46
Epoxy-Coated Specimens									
E7241	24	8.74	19.63	3	5.50	5.63	5.68	5.72	0.09
E7242	24	8.74	19.63	4.7	5.75		5.75		
E7301	30	8.74	25.63	3.0	5.40	5.40	5.40	5.40	0.00
E7363	36	15	28.50	4.0	6.75	6.75	7.50	7.50	0.75
E7361	36	8.74	31.63	5.2	6.60	6.05	6.61	6.06	0.00
E7362*	36	8.74	31.63	5.3	5.50		5.50		
E736SX*	36	8.74	31.63	5.3	5.50	5.50	5.50	5.50	0.00
Average =					5.95		6.14		0.17

* Failed at Fatigued

Table 4.75 (Continued)

Specimen	Peak Stress (ksi)	Stress Range (ksi)	Mean Stress (ksi)	f'c (ksi)	Splitting Load (k)	Average Split-Load (k)	Failure Load (k)	Average Fail Load (k)	Post-Split. Load (k)
Uncoated Specimens									
U11243	24	15.00	16.50	3.0	20.00	20.00	32.24	32.24	12.24
U11241	24	8.74	19.63	3	23.00	25.50	30.00	32.83	7.33
U11242	24	8.74	19.63	4.7	28.00		35.65		
U11303	30	15.00	22.50	4.0	27.29	27.29	37.00	37.00	9.71
U11301	30	8.74	25.63	5.2	24.00	24.50	40.00	39.01	14.51
U11302	30	8.74	25.63	5.3	25.00		38.01		
U1130SX**	30	8.74	25.63	5.2	32.02	32.02	41.96	41.96	9.94
U1130DX	30	8.74	25.63	5.2	21.30	21.30	33.95	33.95	12.65
Average =					24.12		35.79		11.05
Epoxy-Coated Specimens									
E11243	24	15.00	16.50	3.0	23.18	23.18	26.12	26.12	2.94
E11241	24	8.74	19.63	3	20.00	23.75	25.56	26.81	3.06
E11242	24	8.74	19.63	4.7	27.50		28.06		
E11303*	30	15.00	22.50	4.0	21.25	21.25	21.25	21.25	0.00
E11301	30	8.74	25.63	5.2	22.00	22.00	29.88	29.31	7.31
E11302	30	8.74	25.63	5.3	22.00		28.74		
E1130SX	30	8.74	25.63	5.2	23.00	23.00	32.00	32.00	9.00
E1130DX	30	8.74	25.63	5.2	21.39	21.39	21.39	21.39	0.00
Average =					21.33		25.36		2.59

* Failed at Fatigue

** Shear Failure

Table 4.76 c/db, ls/db and E/U Ratios of Splitting Load

Case	Bar #	Cover (inches)	ls (inches)	c/db	ls/db	E/U Split. Load
1	7	2.5	12	2.86	13.71	0.802
2	11	2.5	28	1.77	19.86	0.914
3	6*	2.25	12	3.00	16.00	0.928
4	6*	2.25	10	3.00	13.33	0.818

* Cleary's Tests

Table 4.77 Failure Stresses and Bond Efficiency
(Type A Specimens)

C= 2.38 C/db = 2.72 (use 2.5) Ktr = 2.50 ls = 12 in

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Specimen	Peak Stress (ksi)	Stress Range (ksi)	f'c (ksi)	Failure Load (k)	Failure Stress (ksi)	Bond-Ratio	Bond Stress				Bond Efficiency					
							Orangun Equation	ACI no splice no epoxy	ACI splice no epoxy	ACI epoxy no splice	ACI epoxy splice	Orangun 6/8	6/9	6/10	6/11	ACI Code
U7241	24	8.74	3	5.99	39.10		44.61	34.23	26.33			0.88	1.14	1.48		
E7241	24	8.74	3	5.68	37.21	0.952	44.61	34.23	26.33	22.82	17.56	0.83	1.09	1.41	1.63	2.12
U7242	24	8.74	4.7	7.07	45.10		55.83	42.85	32.96			0.81	1.05	1.37		
E7242	24	8.74	4.7	5.75	37.16	0.824	55.83	42.85	32.96	28.57	21.97	0.67	0.87	1.13	1.30	1.69
U7301	30	8.74	3.0	6.75	43.73		44.61	34.23	26.33			0.98	1.28	1.66		
E7301	30	8.74	3.0	5.40	35.51	0.812	44.61	34.23	26.33	22.82	17.56	0.80	1.04	1.35	1.56	2.02
U7361	36	8.74	5.2	9.20	57.75		58.73	45.07	34.67			0.98	1.28	1.67		
E7361	36	8.74	5.2	6.61	42.22	0.731	58.73	45.07	34.67	30.05	23.11	0.72	0.94	1.22	1.41	1.83
U7362	36	8.74	5.3	8.80	55.32		59.29	45.50	35.00			0.93	1.22	1.58		
E7362	36	8.74	5.3	5.50*	35.55	0.643	59.29	45.50	35.00	30.33	23.33	0.60	0.78	1.02	1.17	1.52
U7363	36	15	4.0	9.00	56.96		51.51	39.53	30.41			1.11	1.44	1.87		
E7363	36	15	4.0	7.50	47.90	0.841	51.51	39.53	30.41	26.35	20.27	0.93	1.21	1.58	1.82	2.36
U736SX	36	8.74	5.2	8.50	53.52		58.73	45.07	34.67			0.91	1.19	1.54		
E736SX	36	8.74	5.2	5.50*	35.55	0.664	58.73	45.07	34.67	30.05	23.11	0.61	0.79	1.03	1.18	1.54
Average Bond Ratio = 0.78							Average Uncoated									
							St dev. Uncoated									
							Average Epoxy-Coated									
							St dev Epoxy-Coated									
U7STAT	-	Static	3.9	6.50	41.89		50.86	39.03	30.02	26.02	20.02	0.82	1.07	1.40		
E7STAT	-	Static	3.9	6.50	41.89	1.000	50.86	39.03	30.02	26.02	20.02	0.82	1.07	1.40	1.61	2.09

* Failed at Fatigued

Table 4.78 Failure Stresses and Bond Efficiency (Type B Specimens)

Specimen	C= 2.5		C/db = 1.77		Ktr = 1.56		ls = 28 in		Bond Efficiency												
	Peak Stress (ksi)	Stress Range (ksi)	f'c (ksi)	Failure Load (k)	Failure Stress (ksi)	Bond-Ratio	Bond Stress						Bond Efficiency								
							Orangun Equation	ACI no epoxy	ACI splice no epoxy	ACI epoxy no splice	ACI epoxy splice	Orangun 6/8	ACI Code								
													6/9	6/10	6/11	6/12					
U11241	24	8.74	3	30.00	42.08		46.11	24.58	18.91			0.91	1.71	2.23							
E11241	24	8.74	3	25.56	36.01	0.86	46.11	24.58	18.91		16.38	12.60	0.78	1.47	1.90	2.20			6/12		
U11242	24	8.74	4.7	35.65	49.15		57.71	30.76	23.66				0.85	1.60	2.08				2.86		
E11242	24	8.74	4.7	28.06	38.90	0.79	57.71	30.76	23.66		20.51	15.78	0.67	1.26	1.64	1.90			2.47		
U11243	24	15.00	3.0	32.24	45.15		46.11	24.58	18.91				0.98	1.84	2.39						
E11243	24	15.00	3.0	26.12	36.77	0.81	46.11	24.58	18.91		16.38	12.60	0.80	1.50	1.94	2.24			2.92		
U11301	30	8.74	5.2	40.00	54.86		60.70	32.36	24.89				0.90	1.70	2.20						
E11301	30	8.74	5.2	29.88	41.23	0.75	60.70	32.36	24.89		21.57	16.59	0.68	1.27	1.66	1.91			2.48		
U11302	30	8.74	5.3	38.01	52.15		61.28	32.67	25.13				0.85	1.60	2.08						
E11302	30	8.74	5.3	28.74	39.68	0.76	61.28	32.67	25.13		21.78	16.75	0.65	1.21	1.58	1.82			2.37		
U11303	30	15.00	4.0	37.00	51.21		53.24	28.38	21.83				0.96	1.80	2.35						
E11303	30	15.00	4.0	21.25 *	29.85	0.58	53.24	28.38	21.83		18.92	14.55	0.56	1.05	1.37	1.58			2.05		
U1130SX	30	8.74	5.2	41.96**	57.49		60.70	32.36	24.89				0.95	1.78	2.31						
E1130SX	30	8.74	5.2	32.00	44.09	0.77	60.70	32.36	24.89		21.57	16.59	0.73	1.36	1.77	2.04			2.66		
U1130DX	30	8.74	4.3	33.95	46.71		55.20	29.42	22.63				0.85	1.59	2.06						
E1130DX	30	8.74	4.3	21.39*	29.81	0.64	55.20	29.42	22.63		19.62	15.09	0.54	1.01	1.32	1.52			1.98		
Average Bond Ratio = 0.75						Average Uncoated															
						St dev. Uncoated															
						Average Epoxy-Coated															
						St dev Epoxy-Coated															
U11STAT	-	Static	3.9	32.60	45.28		52.57	28.02	21.56	18.68	14.37	0.86	1.62	2.10		0.91	1.70	2.21			
E11STAT	-	Static	3.9	25.40	35.50	0.78	52.57	28.02	21.56	18.68	14.37	0.68	1.27	1.65	1.90	2.47	0.05	0.10	0.13		
Average E/U Ratio =						Average Epoxy-Coated															
						St dev Epoxy-Coated															
						1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.78	0.78	0.78	0.78	0.78	0.78			

* Failed at Fatigued

** Shear Failure

Table 4.79 Concrete Compressive Strength and Bond Ratio

f'c (psi)	Bond Ratio	
	Type A	Type B
3000	0.882	0.835
3900 - 4000	0.841	0.583
	1.000*	0.784*
4300	-	0.638
4700	0.824	0.791
5200-5300	0.679	0.760

* Static Loading Test

Table 4.80 Stress Range and Bond Ratio

Stress Range (Ksi)	Bond Ratio	
	Type A	Type B
8.74	0.771	0.761
15	0.841	0.699
Static	1.000	0.784

Table 4.81 Failure Stresses and Bond Efficiency
(Cleary and Ramirez Study)

1	2	3	4	5	6	7	8	9	10	11	12	13
Specimen	Failure Stress (ksi)	Bond-Ratio	Bond Stress					Bond Efficiency				
			Orangun Equation	ACI No splice	ACI Splice	ACI epoxy no splice	ACI epoxy splice	Orangun 2/4	ACI Code			
									2/5	2/6	2/7	2/8
U12410A	64.60		59.70	55.90	43.00			1.082	1.156	1.502		
E12410A	52.70	0.816	59.70	55.90	43.00	46.58	35.83	0.883	0.943	1.226	1.131	1.471
U12410B	60.60		60.40	56.50	43.46			1.003	1.073	1.394		
E12410B	53.10	0.876	60.40	56.50	43.46	47.08	36.22	0.879	0.940	1.222	1.128	1.466
U12415A	62.20		59.70	55.90	43.00			1.042	1.113	1.447		
E12415A	53.70	0.863	59.70	55.90	43.00	46.58	35.83	0.899	0.961	1.249	1.153	1.499
U12415B	64.60		60.40	56.50	43.46			1.070	1.143	1.486		
E12415B	56.40	0.873	60.40	56.50	43.46	47.08	36.22	0.934	0.998	1.298	1.198	1.557
U12410C	68.90		65.30	61.20	47.08			1.055	1.126	1.464		
E12410C	63.10	0.916	65.30	61.20	47.08	51.00	39.23	0.966	1.031	1.340	1.237	1.608
U12415C	64.10		65.30	61.20	47.08			0.982	1.047	1.362		
E12415C	59.80	0.933	65.30	61.20	47.08	51.00	39.23	0.916	0.977	1.270	1.173	1.524
U10710A	61.70		65.90	59.00	45.38			0.936	1.046	1.359		
E10710A	51.30		65.90	59.00	45.38	49.17	37.82	0.778	0.869	1.130	1.043	1.356
U12710A	63.00		75.60	70.80	54.46			0.833	0.890	1.157		
+ E12710A	60.30	0.957	68.90	68.90				0.914	0.914			
+ E12710A	60.30		75.60	70.80	54.46	59.00	45.38	0.798	0.852	1.107	1.022	1.329
			66.60	66.60				0.905	0.905			
U12715A	63.10		76.40	71.60	55.08			0.826	0.881	1.146		
+ E12715A	52.30	0.848	68.90	68.90				0.916	0.916			
+ E12715A	52.30		76.40	71.60	55.08	59.67	45.90	0.685	0.730	0.950	0.877	1.139
			66.60	66.60				0.785	0.785			
E124SA	49.60		60.40	56.50	43.46	47.08	36.22	0.821	0.878	1.141	1.053	1.369
E107SA	43.10		64.90	58.10	44.69	48.42	37.24	0.664	0.742	0.964	0.890	1.157
E107SB	42.20		68.20	61.10	47.00	50.92	39.17	0.619	0.691	0.898	0.829	1.077
E127SA	53.90		76.40	71.60	55.08	59.67	45.90	0.705	0.753	0.979	0.903	1.174
+ E127SB	59.50		66.60	66.60				0.809	0.809			
+ E127SB	59.50		76.40	71.60	55.08	59.67	45.90	0.779	0.831	1.080	0.997	1.296
			66.60	66.60				0.893	0.893			
Average Bond Ratio = 0.89			Average Uncoated					0.981	1.053	1.369	-	-
			St dev. Uncoated					0.097	0.103	0.133	-	-
			Average Epoxy-Coated					0.860	0.940	1.199	1.107	1.439
			St dev Epoxy-Coated					0.089	0.098	0.119	0.117	0.143
Static Loading Test								0.718	0.779	1.012	0.935	1.215
								0.083	0.075	0.097	0.090	0.117

Table 4.82 Summary of Bond Efficiency

Specimens	Loading	Bar Type	Bond Efficiency											
			Orangun				no splice, no epoxy				splice, no epoxy			
			Average	Std. Dev	no splice, no epoxy		Average	Std. Dev	splice, no epoxy		Average	Std. Dev	epoxy, no splice	
Type A	Cyclic	U	0.94	0.09	1.23	0.12	1.60	0.16	-	-	-	-	-	-
	Cyclic	E	0.74	0.12	0.96	0.16	1.25	0.21	1.44	0.24	1.87	0.31	-	-
	Static	U	0.82	-	1.07	-	1.40	-	-	-	-	-	-	-
	Static	E	0.82	-	1.07	-	1.40	-	1.61	-	2.09	-	-	-
Type B	Cyclic	U	0.91	0.05	1.70	0.10	2.21	0.13	-	-	-	-	-	-
	Cyclic	E	0.68	0.09	1.27	0.18	1.65	0.23	1.90	0.26	2.47	0.34	-	-
	Static	U	0.86	-	1.62	-	2.10	-	-	-	-	-	-	-
	Static	E	0.68	-	1.27	-	1.65	-	1.90	-	2.47	-	-	-
Cleary and Ramirez [11]	Cyclic	U	0.981	0.097	1.053	0.103	1.369	0.133	-	-	-	-	-	-
	Cyclic	E	0.860	0.089	0.940	0.098	1.199	0.119	1.107	0.117	1.439	0.143	-	-
	Static	U	-	-	-	-	-	-	-	-	-	-	-	-
	Static	E	0.718	0.083	0.779	0.075	1.012	0.097	0.935	0.090	1.215	0.117	-	-

U = Uncoated E= Epoxy-Coated

Table 4.83 Bond Efficiency With Proposed ACI 318-89 Modification Factor

1	2	3	4	5	6	7	8	9	10	11	12
Specimen	Type A Specimens					Type B Specimens					
	f'c (ksi)	Failure Stress (ksi)	Bond Stress		Bond Efficiency Proposed 3/5	Specimen	f'c (ksi)	Failure Stress (ksi)	Bond Stress		Bond Efficiency Proposed 9/11
			ACI no splice no epoxy	ACI Proposed					ACI no splice no epoxy	ACI Proposed	
U7241	3	39.10	34.23	26.33	1.48	U11241	3	42.08	24.58	18.91	2.23
E7241	3	37.21	34.23	25.36	1.47	E11241	3	36.01	24.58	18.21	1.98
U7242	4.7	45.10	42.85	32.96	1.37	U11242	4.7	49.15	30.76	23.66	2.08
E7242	4.7	37.16	42.85	31.74	1.17	E11242	4.7	38.90	30.76	22.79	1.71
U7301	3.0	43.73	34.23	26.33	1.66	U11243	3.0	45.15	24.58	18.91	2.39
E7301	3.0	35.51	34.23	25.36	1.40	E11243	3.0	36.77	24.58	18.21	2.02
U7361	5.2	57.75	45.07	34.67	1.67	U11301	5.2	54.86	32.36	24.89	2.20
E7361	5.2	42.22	45.07	33.38	1.26	E11301	5.2	41.23	32.36	23.97	1.72
U7362	5.3	55.32	45.50	35.00	1.58	U11302	5.3	52.15	32.67	25.13	2.08
E7362	5.3	35.55	45.50	33.70	1.05	E11302	5.3	39.68	32.67	24.20	1.64
U7363	4.0	56.96	39.53	30.41	1.87	U11303	4.0	51.21	28.38	21.83	2.35
E7363	4.0	47.90	39.53	29.28	1.64	E11303	4.0	29.85	28.38	21.02	1.42
U736SX	5.2	53.52	45.07	34.67	1.54	U1130SX	5.2	57.49	32.36	24.89	2.31
E736SX	5.2	35.55	45.07	33.38	1.06	E1130SX	5.2	44.09	32.36	23.97	1.84
Average Uncoated					1.60	Average Uncoated					2.21
Stdev. Uncoated					0.16	Stdev. Uncoated					0.13
Average Epoxy-Coated					1.29	Average Epoxy-Coated					1.71
Stdev Epoxy-Coated					0.22	Stdev Epoxy-Coated					0.24
U7STAT	3.9	41.89	39.03	30.02	1.40	U11STAT	3.9	45.28	28.02	21.56	2.10
E7STAT	3.9	41.89	39.03	28.91	1.45	E11STAT	3.9	35.50	28.02	20.76	1.71

Table 4.84 Bond Efficiency With Proposed ACI 318-89 Modification Factor
(Cleary and Ramirez Study)

1	2	3	4	5
Specimen	Failure Stress (ksi)	Bond Stress		Bond Efficiency
		ACI no splice no epoxy	ACI Proposed	ACI Proposed 2/4
U12410A	64.60	55.90	43.00	1.502
E12410A	52.70	55.90	41.41	1.273
U12410B	60.60	56.50	43.46	1.394
E12410B	53.10	56.50	41.85	1.269
U12415A	62.20	55.90	43.00	1.447
E12415A	53.70	55.90	41.41	1.297
U12415B	64.60	56.50	43.46	1.486
E12415B	56.40	56.50	41.85	1.348
U12410C	68.90	61.20	47.08	1.464
E12410C	63.10	61.20	45.33	1.392
U12415C	64.10	61.20	47.08	1.362
E12415C	59.80	61.20	45.33	1.319
U10710A	61.70	59.00	45.38	1.359
E10710A	51.30	59.00	43.70	1.174
U12710A	63.00	70.80	54.46	1.157
+		68.90		
E12710A	60.30	70.80	52.44	1.150
+		66.60		
U12715A	63.10	71.60	55.08	1.146
+		68.90		
E12715A	52.30	71.60	53.04	0.986
+		66.60		
E124SA	49.600	56.50	41.85	1.185
E107SA	43.100	58.10	43.04	1.001
E107SB	42.200	61.10	45.26	0.932
E127SA	53.900	71.60	53.04	1.016
+		66.60		
E127SB	59.500	71.60	53.04	1.122
+		66.60		
Average Uncoated				1.369
St dev. Uncoated				0.133
Average Epoxy-Coated				1.245
St dev. Epoxy-Coated				0.124
Static Loading Test			Average	1.051
			Stdev	0.101

+ indicates values for steel yielding

Table 4.85 Comparison of Bond Efficiency

Specimens	Loading	Bar Type	Bond Efficiency				Diff. (%)
			ACI 318-89, Current		ACI, Proposed		
			Average	Std. Dev	Average	Std. Dev	
Type A	Cyclic	U	1.60	0.16	1.60	0.16	0.00
	Cyclic	E	1.87	0.31	1.29	0.22	30.87
	Static	U	1.40	-	1.40	-	0.00
	Static	E	2.09	-	1.45	-	30.68
Type B	Cyclic	U	2.21	0.13	2.21	0.13	0.00
	Cyclic	E	2.47	0.34	1.71	0.24	30.77
	Static	U	2.10	-	2.10	-	0.00
	Static	E	2.47	-	1.71	-	30.76
Cleary and Ramirez [ref]	Cyclic	U	1.369	0.133	1.369	0.133	0.00
	Cyclic	E	1.439	0.143	1.245	0.124	13.47
	Static	U	-	-	-	-	-
	Static	E	1.215	0.117	1.051	0.101	13.46

U = Uncoated E= Epoxy-Coated

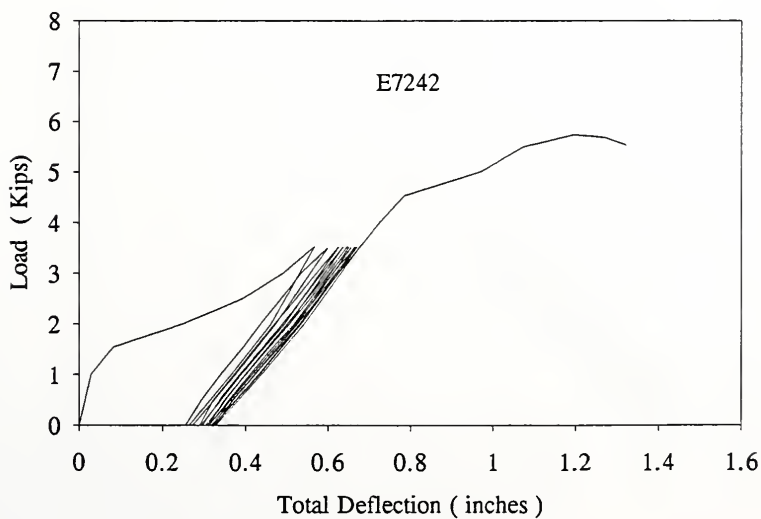
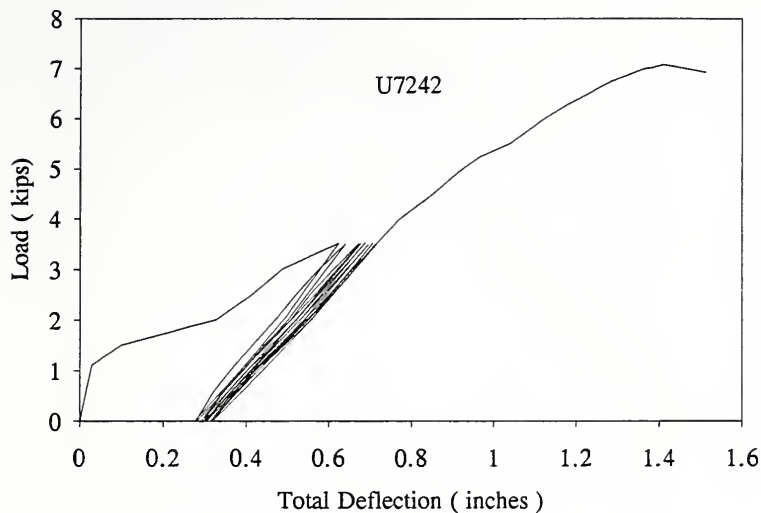


Figure 4.1 Cyclic Load-Deflection, Series 7242

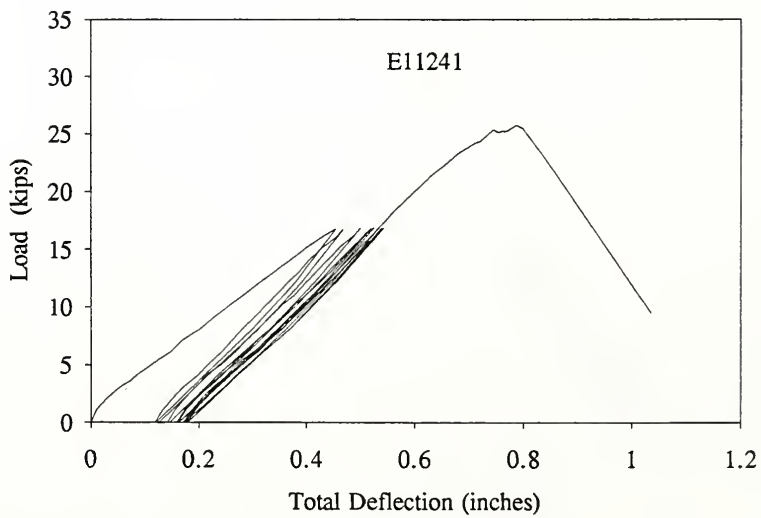
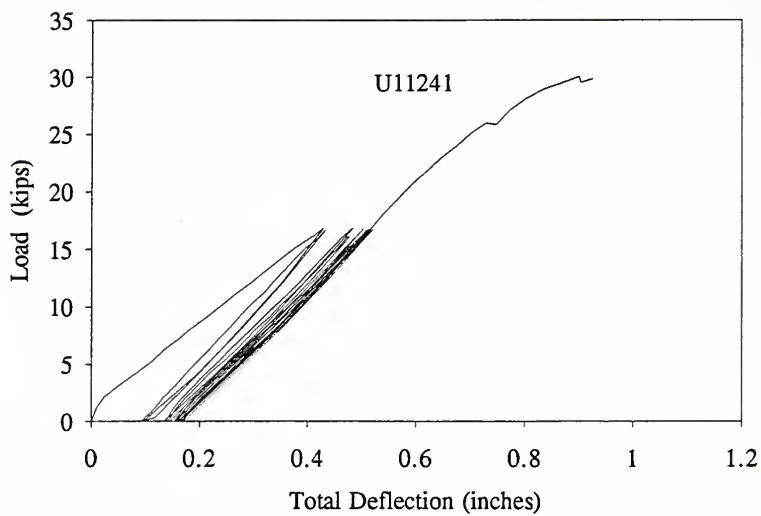


Figure 4.2 Cyclic Load - Deflection, Series 11241

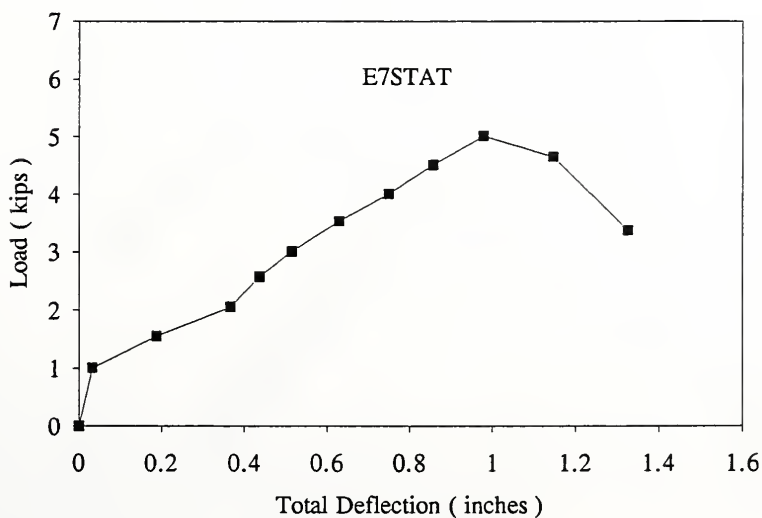
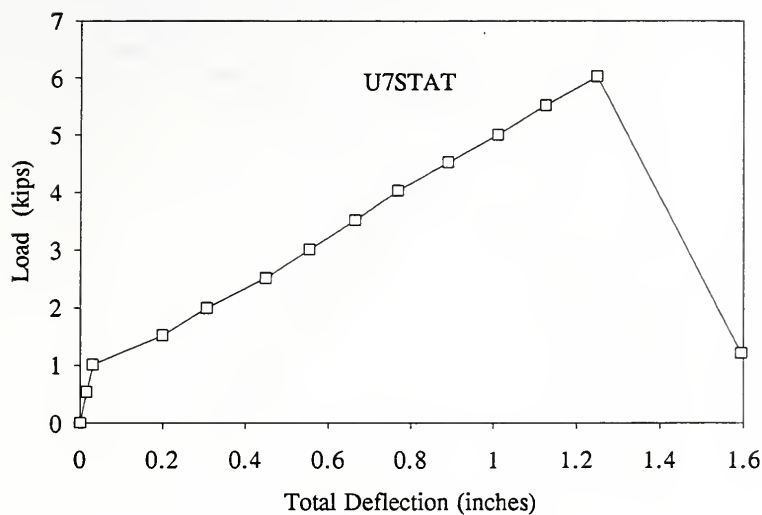


Figure 4.3 Load - Deflection, Series 7STAT

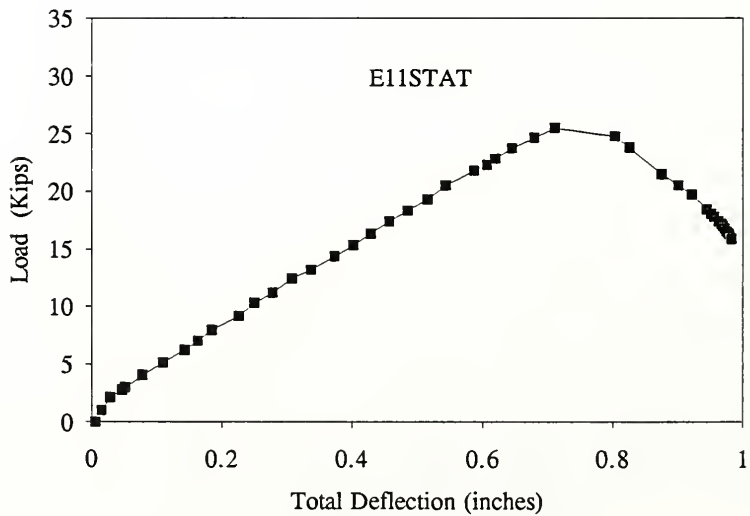
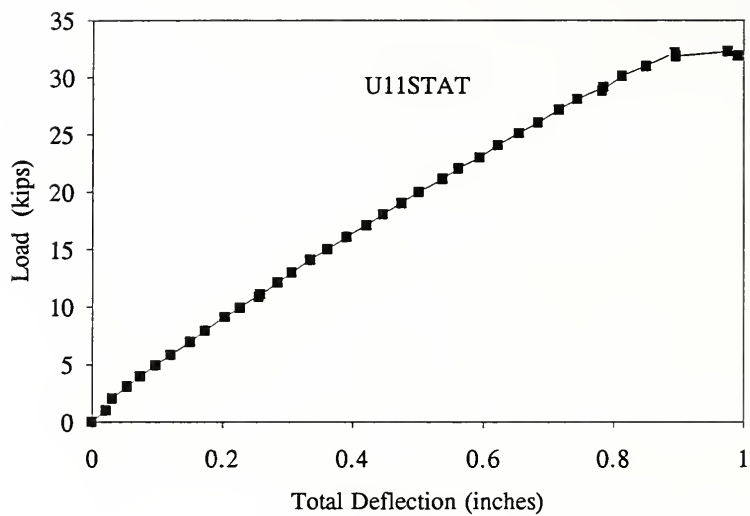


Figure 4.4 Cyclic Load - Deflection, Series 11STAT

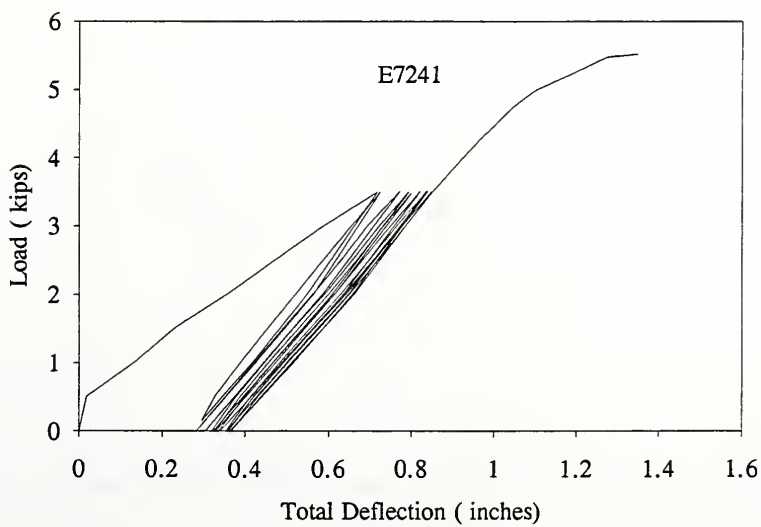
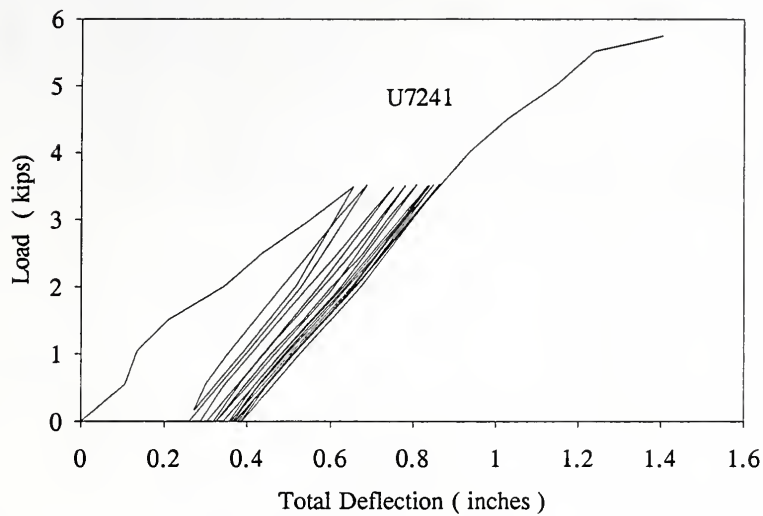


Figure 4.5 Cyclic Load - Deflection, Series 7241

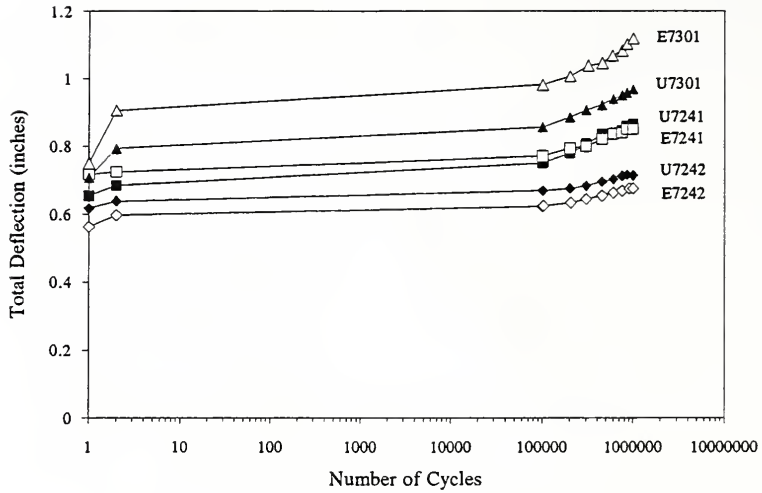


Figure 4.6 Total Deflection versus Number of Cycles
Series 7241, 7242, 7301, $P = 3.5$ k

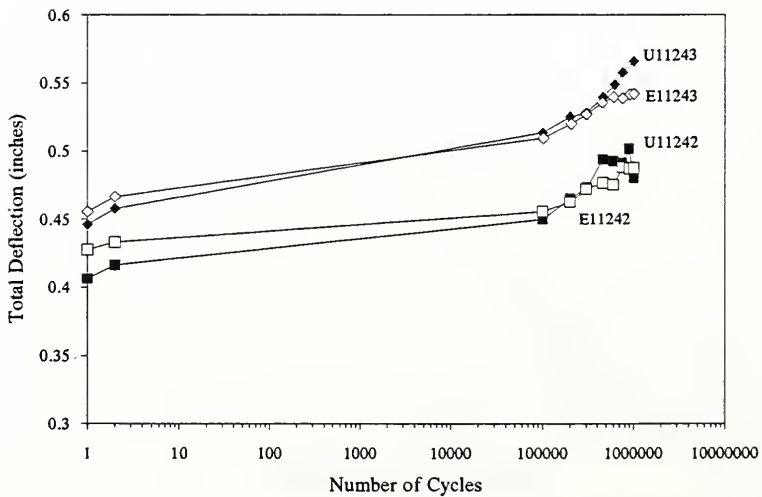


Figure 4.7 Total Deflection versus Number of Cycles
Series 11242, 11243, $P =$ Peak Repeating Load

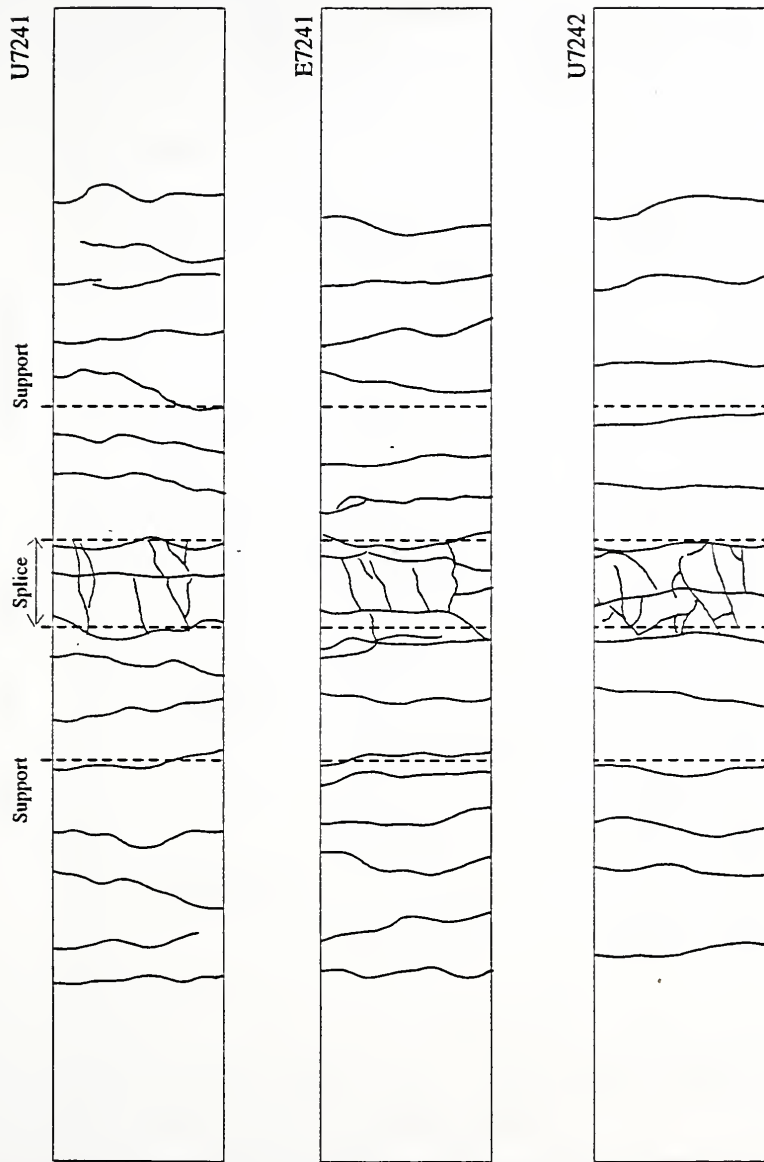


Figure 4.8 Crack Patterns at Failure, Type A Specimens

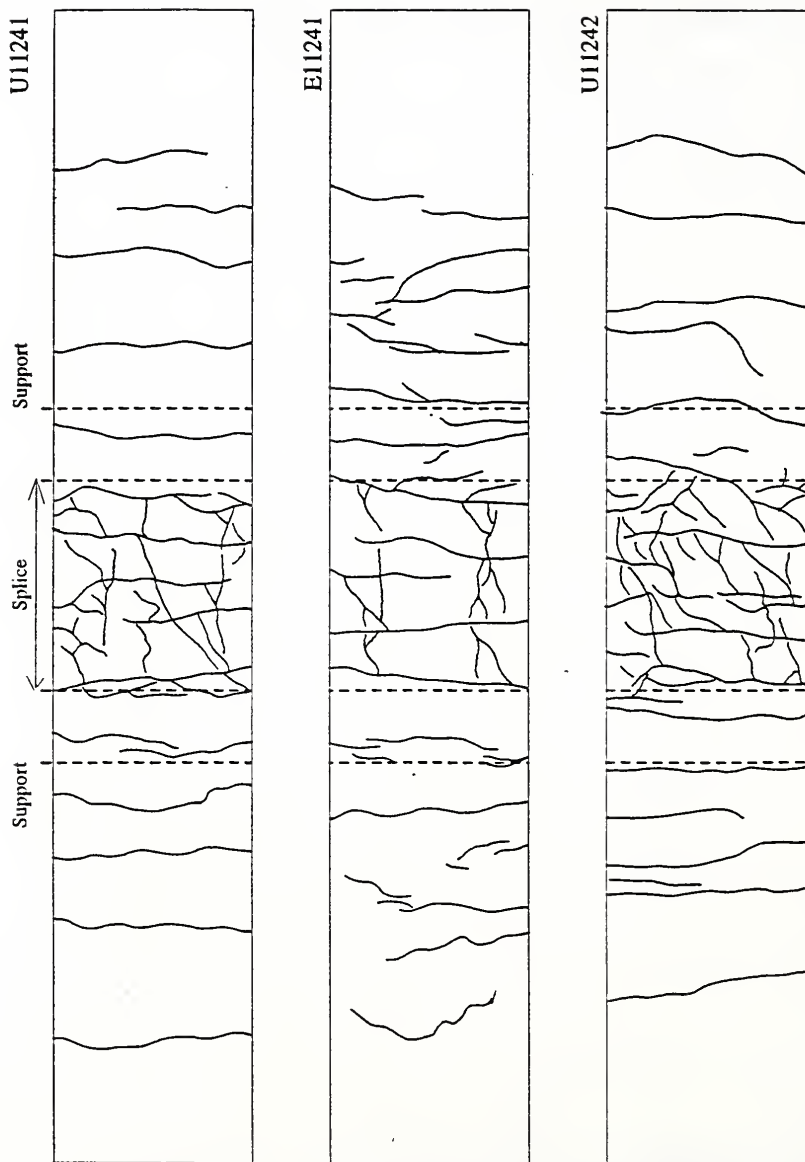


Figure 4.9 Crack Patterns at Failure, Type B Specimens

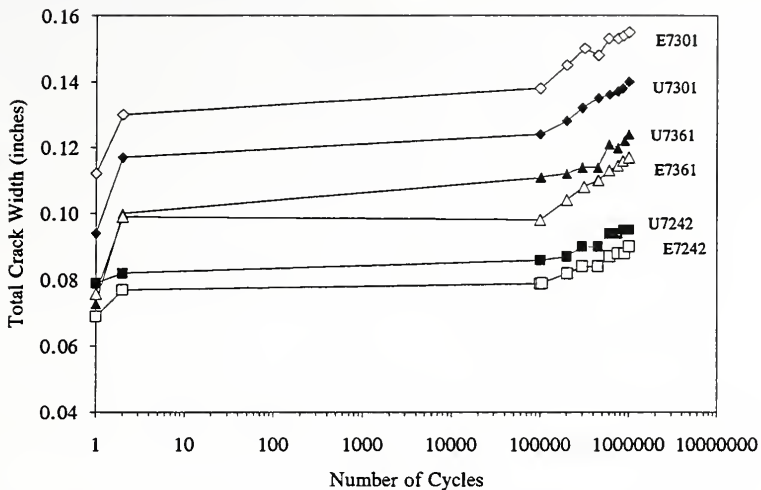


Figure 4.10 Total Crack Widths versus Number of Cycles, $P = 3.5$ k
Series 7301, 7361, 7242

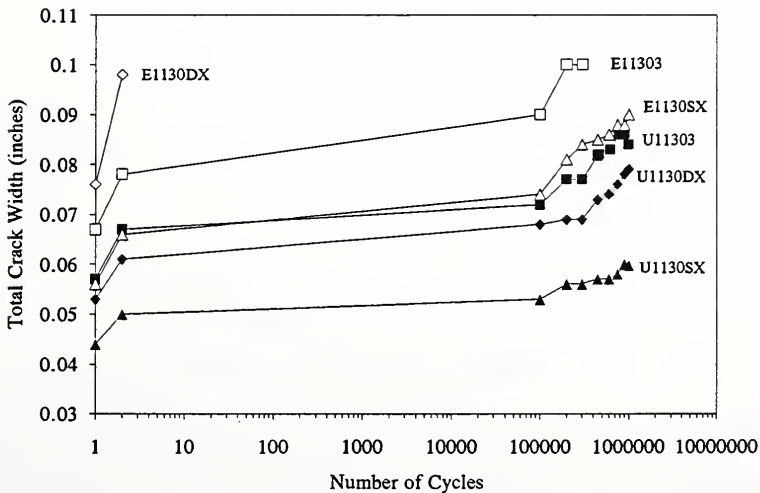


Figure 4.11 Total Crack Widths versus Number of Cycles
 $P = 16$ k, Series 11303, 1130SX, 1130DX

CHAPTER 5 FIELD EVALUATION

5.1 Purpose and Scope

The Field Phase of the research study is aimed at the condition assessment of a representative sample of concrete bridge decks and slabs reinforced with epoxy-coated steel in Indiana. A total of six bridges throughout the state of Indiana were selected for the evaluation. The bridges included in the evaluation were selected to represent a cross section of environmental conditions, traffic, and intensity of salt application. The sample included the first bridge deck in Indiana reinforced with epoxy-coated steel. The field study addresses the performance of decks supported on a more flexible system (steel girder) as well as more rigid support conditions (precast prestressed girders) and concrete slabs. The site selection was fully coordinated with personnel from INDOT. Evaluation of concrete core samples for compressive strength and concrete powder samples for chloride content was conducted by the Material and Testing Division from INDOT. The support and expertise provided by INDOT is deeply appreciated. The actual location by county of the bridges selected is shown in Figure 5.1.

5.2 Brief Description of Bridge Decks Evaluated

The first bridge selected for evaluation was built in 1985. The bridge is located in downtown Indianapolis over the White River. The structure is a six span continuous composite steel box girder with a maximum span length of 206 feet. This bridge represents the case of a deck on a flexible superstructure in the central part of the state

subjected to heavy urban traffic and severe deicing-salt exposure. The second bridge is located in downtown South Bend. The structure was built in 1983 and has a maximum span length of 90 feet. The structure is a four span continuous composite bridge deck supported on precast prestressed AASHTO girders and represents a case of concrete bridge deck built on a more rigid support system. This structure is subjected to significant urban traffic and severe salt application. The third structure is located a few miles south of South Bend. It was built in 1980 and consists of three span continuous welded girder bridge with composite deck subjected to heavy truck traffic and heavy salt exposure condition. The fourth structure is a three span skewed continuous reinforced concrete slab bridge built in 1985. The maximum span length is 46 feet. The structure is subjected to moderate traffic and moderate deicing salt application. The fifth structure is a three span continuous bridge deck supported on continuous steel girders located in the city of Gary in the northern part of the state. This bridge was built in 1980 with a maximum span length of 64'-6. The concrete deck was built using stay-in-place metal forms. The bridge is subjected to heavy industrial traffic with heavy de-icing salt application. The sixth bridge deck selected in this study is supported on continuous prestressed concrete I-beams (Type III). The bridge was built in 1976, it has three spans with a maximum span length of 73'-9 subjected to light to moderate truck traffic and moderate salt exposure. A summary of the bridge information and the traffic data are presented in Tables 5.1 and 5.2 respectively.

5.3 Field Evaluation Procedures

The field evaluation included the following procedures:

1. Identify any delaminated and spalling areas by close visual inspection and using chain drag.
2. Detailed mapping of the observed cracking as well as delamination and spalling area on the selected lane.
3. Evaluate the concrete cover using an R-meter (focused electromagnetic field) to obtain the concrete cover.
4. Core samples taken with or without reinforcement for evaluation of concrete compressive strength, concrete cover, unit weight, and visual inspection of the conditions of the epoxy-coated bar sections.
5. Concrete powder sampled at selected points and at various depths for laboratory determination of chloride content.

During the field inspection, detailed mapping of delamination and spalling areas as well as crack patterns were made. Crack widths were estimated using a crack width comparator card. The delamination and spalling areas were identified by close visual inspection and with the aid of a drag chain. Positions of reinforcement were identified by using an R-meter. Core samples with or without top layer of reinforcement were then taken for laboratory investigation. The chloride contents were determined through the laboratory analysis of pulverized samples of concrete taken from holes drilled in the deck. Concrete powder samples were taken at the level of 0-1 inches, 1-2 inches, 2-3 inches, and 3-4 inches. Diameters of the holes for each depth are 1 1/4

inches, 1 inch, 3/4 inches, and 3/4 inches respectively.

5.4 Summary Results

The crack patterns, core and chloride sample locations for the bridges studied are shown in Figures 5.2 through 5.53. The maximum measured crack widths ranged from 0.025 to 0.060 in. Corings enabled the examination of the condition of the reinforcing steel as well as the measurement of the actual cover depth. The average concrete cover ranged from 2.4 to 3.82 inches. Inspections of the conditions of steel extracted from cores show no indication of rusting nor debonding on any of the bars. The coating was difficult to strip even with a knife. From visual inspection of samples from which the coating has been stripped mechanically, no sign of underfilm corrosion was observed.

Tables 5.3 through 5.8 show the results of laboratory tests and measurement of core and concrete powder samples of the bridges studied. The laboratory works were performed by the Division of Materials and Testing, INDOT. The laboratory works included the determination of concrete cover from core samples, concrete compressive strength, unit weight, and chloride contents for various depths. A summary of the average values of core strength, calculated cylinder strength, unit weight, concrete cover, and chloride content is presented in Table 5.9.

The average compressive strength of the 6 inch core tests ranged from 5495 psi to 7483 psi and converted to a cylinder strength the range was from 4670 psi to 6360 psi. The average concrete cover ranged from 2.40 inches to 3.82 inches. The average

chloride content at level 0-1 inches ranged from 5.93 to 17.76 lb/cu.yd; at level 1-2 inches ranged from 2.17 to 12.15 lb/cu.yd; 1.09 to 4.99 lb/cu.yd at level 2-3 inches, and 0.80 to 3.97 lb/cu.yd at level 3-4 inches. The maximum measured crack widths ranged from 0.025 to 0.060 in.

5.5 Discussion of Findings

At the level of top reinforcement, except for the Bartholomew County bridge, the chloride contents were found to be above the threshold value of 2.0 lb/cu.yd [27]. This indicates that a potential active corrosive environment exists. Inspection of the steel samples from coring has shown no sign of corrosion. It also showed reasonable durability, no debonding of the coating was evident in any of the steel samples. Results of tests to determine chloride concentrations show that chloride concentrations substantially decreased with every 1 inch of increment in depth. This indicates that an increase in concrete cover will significantly reduce the risk of corrosion.

Similar results were reported by Mckeel [28]. From the evaluation during construction and through 13 years of service of two bridges in Virginia, it was concluded that the combination of cover and epoxy-coated reinforcement has provided excellent protection against corrosion. No sign of significant corrosion and debonding of the coating were found despite the poor initial state of the coating and its exposure to the elements from the onset of construction until placement of the deck concrete.

Beside the structural concern of the bond properties of epoxy-coated steel, other significant issues concerning epoxy-coated steel are the effectiveness and

durability of epoxy-coated reinforcement. In the last few years, there has been serious concern about the effectiveness and long term durability of the epoxy-coated steel as a corrosion protection system.

Smith, Kessler and Powers [29], investigated seven bridge structures in the Florida Keys. Significant corrosion was found of the epoxy-coated rebars in four of the five major bridge substructures. It was found that corrosion occurred both in fabricated and straight epoxy-coated rebars and coating after fabrication did not significantly improve corrosion resistance. Disbondment occurred in "perfect" condition bars and in the bars coated after fabrication. It was concluded that epoxy-coated rebar will not provide suitable long-term protection against corrosion in the marine splash zone.

In 1990, Kenneth C. Clear, Inc., a consulting firm of materials and corrosion specialists [30] stated that epoxy coated rebar technology is flawed and will not assure adequate long term field performance in severe chloride environments, especially those involving continuous or very frequent wetting of the concrete. The failure of the epoxy coating through means such as cathodic disbondment and the loss of the epoxy's insulative properties has also been reported. It was concluded that the system "can no longer be considered a viable primary protective system for North American bridge structures in corrosive environments with expected maintenance-free lives in excess of about 15 years in northern environments or more than 5 years in hot, salty and moist southern exposures." Furthermore, the consultant recommended against the continued usage of epoxy coated reinforcing steel as the primary protection in adverse

environments for structures for low-maintenance lives in excess of 5 years (southern) or 15 years (northern). Because of the controversy and the broad implications of the issue, the effectiveness and long-term durability issues of epoxy-coated bars have gained the attention of researchers and institutions. Efforts are being made to gain a better understanding of the long-term durability and effectiveness of epoxy-coated steel. [28, 31, 32].

In 1992, a short term study on the structural effects of epoxy coating disbondment, if such disbondment does take place, was conducted by the Office of Engineering and Highway Operations Research and Development, Federal Highway Administration [32]. The disbondment was induced by means of electrochemical process which resulted in a significant degree of disbondment between 20 and 30%. Three types of slab specimens with plain uncoated rebars, untreated epoxy-coated rebars, and disbonded epoxy-coated bars were used. The results of the flexural tests indicated no difference in negative moment capacities and some differences in the positive moment capacities between the three test groups but the differences were not considered large enough to constitute a structural safety problem. It was found that there were measurable differences between the results of pull-out tests conducted with plain bars, untreated epoxy-coated bars, and disbonded epoxy-coated bars, however, the resistance of the test specimens with disbonded bars was still within the specified acceptable limits. It was concluded that 20 to 30 % of disbondment between the epoxy coating and its steel substrate for bars used as the main flexural reinforcement of one-way slab does not compromise the slab's flexural capacity.

5.6 Summary

A field evaluation of six bridges has been carried out. Although it is limited in scope, and the bridges being studied ranged from six to eighteen years of service. Data gathered in this field study can be useful to address the effectiveness and durability of epoxy-coated steel in Indiana.

Several important findings from this phase of the overall study can be summarized as follows:

1. Chloride content is significantly decreased with small increases in concrete cover
2. Except for Bartholomew County bridge, all the other five bridge decks surveyed were under exposure to chloride contents well above the commonly accepted corrosion threshold of the bridge decks studied.
3. No sign of debonding of the coating and corrosion was observed in the reinforcement in the bridge decks studied.

Based on the findings of this study, it may be concluded that the combination of adequate cover and the use of epoxy-coated steel has provided a good corrosion protection of the bridge decks surveyed to date. This field study has once again shown the importance of adequate concrete cover to reduce the risk of corrosion. Extra cover also provides improvement in the anchorage of the bars. Larger cover to diameter ratios are recommended in harsh environments to reduce the crack opening and should not be reduced with the expectation that the epoxy-coating will be the sole corrosion protection system. Adequate inspection, finishing and curing represent solid

construction practice and will lead to durable concrete. The use, proper manufacturing and handling of epoxy-coated bars are but a few of the aspects related to durable concrete bridge decks.

As there is doubt on the long-term durability of epoxy-coating, and the broad impact that it may cause, further efforts should focus on continuous research in this area.

Table 5.1 Summary of Bridge Information

Bridge Number	Location	Bridge Type	Span Max	Traffic	Deicing Salt Exposure
40-49-7032	Downtown Indianapolis (US-40, Marion 1985)	Six span continuous composite steel box girder bridge	206'-0	Heavy urban	Severe
20-71-6538	Downtown South Bend (US-2, St. Joseph, 1983)	Four span continuous composite pre-cast prestressed AASHTO girder	90'-0	Significant urban	Severe
31-50-2540	South of the City of South Bend (Marshall, US 31, 1980)	Three span continuous welded girder bridge with a composite concrete deck	62'-0	Heavy truck	Heavy
7-03-6797	Bartholomew County (S.R. 7, 1985)	Three span skewed continuous reinforced concrete slab bridge	46'-0	Moderate truck	Moderate
912-45-6599	City of Gary, Indiana (Lake, SR. 912, 1980)	Three span continuous composite steel girder bridge	64'-6	Heavy industrial	Heavy
7-40-6527	Jennings County (S.R. 7, 1976)	Continuous prestressed concrete I beam (Type III)	73'-9	Light to moderate truck	Moderate

Table 5.2 Traffic Data

Bridge	A.D.T. (V.P.D.)	A.D.T. Projected (V.P.D.)	D.H.V (V.P.D.)	Trucks	Design Speed (mph)	Access Control
Downtown Indianapolis	27,530 (1982)	44,390 (2002)	3,995 (2002)	D.H.V. 4 % A.D.T. 5 %	40	None
Downtown South Bend	11,015 (1976)	19,825 (1996)	1,190 (1996)	6 %	40	None
South of the City of South Bend	17,080 (1978)	29,480 (1996)	-	D.H.. V. 10 % A.D.T. 17 %	40	None
Bartholomew County	5,680 (1983)	9,770 (2004)	977 (2004)	D.H.V. 7 % A.D.T. 12 %	70	-
Gary, Indiana	14,800 (1975)	25,250 (1995)	3,170 (1995)	-	50	Full
Jennings County	2,200 (1972)	4,420 (1992)	-	D.H.V. 7 % A.D.T. 17 %	60	None

ADT = Average Daily Traffic

VPD = Vehicles Per Day

DHV = Design Hourly Volume

Table 5.3 Core Compressive Strength, Unit Weight,
Concrete Cover and Chloride Content
Bridge # 40-49-7032, Marion County

Core Number	Span	Minimum Compressive Strength (psi)	Unit Weight (lb/cu.ft)	Concrete Cover (in)	Sample Number	Span	Chloride Content (lb/cu.yd)			
							Level			
							A	B	C	D
							0-1 in.	1-2 in.	2-3 in.	3-4 in.
1	I	-	-	-	1	VI	3.56	1.22	1.50	0.95
2	I	6080	145.4	2.70	2	V	3.48	2.38	1.34	0.91
3	I	6320	148.1	2.20	3	IV	12.28	6.40	2.47	0.61
4	II	6100	146.1	2.20	4	III	9.09	1.97	1.36	1.14
5	II	4930	142.5	2.40	5	II	4.59	0.97	1.25	1.09
6	IV	6330	149.3	2.80	6	I	6.74	2.55	1.17	1.08
7	IV	6330	149.2	3.00	7	I	4.14	0.87	0.77	0.92
8	V	5100	144.5	2.70	8	II	3.91	1.19	0.98	1.23
9	V	7020	147.1	2.50	9	III	9.33	3.34	0.90	1.31
10	VI	6210	142.4	2.00	10	IV	2.24	1.08	1.26	1.69
11	VI	6370	145.7	1.90	11	V	7.87	1.15	1.18	1.45
12	IV	6570	147.0	1.60	12	VI	3.88	2.98	3.60	1.79
13	IV	6110	144.3	2.20						
14	II	7290	150.0	3.00						
15	I	3770	144.3	2.40						
Average		6038	146.1	2.40	Average		5.93	2.17	1.48	1.18

Table 5.4 Core Compressive Strength, Unit Weight ,
Concrete Cover, and Chloride Content
Bridge # 20-71-6538, St. Joseph County

Core Number	Span	Minimum Compressive Strength (psi)	Unit Weight (lb/cu.ft)	Concrete Cover (in)	Sample Number	Span	Chloride Content (lb/cu.yd)			
							Level			
							A	B	C	D
							0-1 in.	1-2 in.	2-3 in.	3-4 in.
BN	B-North	8280	152.3	1.60	1	E-North	15.90	10.82	4.71	4.06
BS	B-South	8460	152.8	3.30	2	D-North	11.74	4.71	3.40	3.11
CN	C-North	7030	149.9	3.00	3	C-North	11.25	4.20	3.14	3.02
CS	C-South	7970	152.1	3.80	4	B-North	20.86	7.85	4.03	4.50
DN	D-North	8040	148.3	3.30	5	E-South	11.45	7.36	2.71	2.97
DS	D-South	7540	151.0	3.60	6	D-South	14.40	8.61	5.61	4.21
EN	E-North	6780	152.0	4.30	7	C-South	14.68	6.19	3.51	3.54
ES	E-South	5760	151.2	2.80	8	B-South	12.49	5.34	1.84	2.10
					9	C-South	14.84	8.88	4.66	8.24
Average		7483	151.2	3.21	Average		14.18	7.11	3.73	3.97

Table 5.5 Core Compressive Strength, Unit Weight ,
Concrete Cover, and Chloride Content
Bridge # 31-50-2540, Marshall County

Core Number	Span	Minimum Compressive Strength (psi)	Unit Weight (lb/cu.ft)	Concrete Cover (in)	Sample Number	Span	Chloride Content (lb/cu.yd)			
							Level			
							A 0-1 in.	B 1-2 in.	C 2-3 in.	D 3-4 in.
AW	A-West	5990	148.8	2.50	1	C-East	19.27	16.77	5.63	1.82
BE	B-East	7160	151.0	2.60	2	B-East	23.12	12.00	1.71	1.26
BW	B-West	6190	148.3	2.30	3	A-East	25.56	14.66	6.36	2.63
CE	C-East	7370	151.0	2.80	4	C-West	15.15	15.12	0.99	1.03
CW	C-West	5910	145.6	2.00	5	B-West	1.91	8.06	1.88	1.01
					6	A-West	18.71	7.84	1.85	1.32
					7	B-West	20.6	10.61	4.04	2.17
Average		6524	148.94	2.44	Average		17.76	12.15	3.21	1.61

Table 5.6 Core Compressive Strength, Unit Weight
Concrete Cover, and Chloride Content
Bridge # 7-03-6797, Bartholomew County

Core Number	Span	Minimum Compressive Strength (psi)	Unit Weight (lb/cu.ft)	Concrete Cover (in)	Sample Number	Span	Chloride Content (lb/cu.yd)			
							Level			
							A	B	C	D
							0-1 in.	1-2 in.	2-3 in.	3-4 in.
1N	1-North	7430	153.5	3.80	1N	1-North	5.17	1.38	0.92	0.70
2NA	2-North	6970	165.5	4.00	2N	2-North	7.70	2.40	1.26	0.85
2NB	2-North	6650	158.0	3.80	3N	3-North	7.88	2.44	0.81	0.70
3N	3-North	6820	149.3	3.50	1S	1-South	5.54	1.71	0.68	0.72
S1	1-South	5310	155.8	3.80	2S	2-South	6.62	2.18	0.79	0.70
S2	2-South	6490	157.6	4.00	3S	3-South	9.90	6.61	2.09	1.13
S3	3-South	6780	144.9	-						
Average		6636	154.9	3.82	Average		7.14	2.79	1.09	0.80

Table 5.7 Core Compressive Strength, Unit Weight
Concrete Cover, and Chloride Content
Bridge # 912-45-6599, Lake County

Core Number	Span	Minimum Compressive Strength (psi)	Unit Weight (lb/cu.ft)	Concrete Cover (in)	Sample Number	Span	Chloride Content (lb/cu.yd)			
							Level			
							A	B	C	D
							0-1 in.	1-2 in.	2-3 in.	3-4 in.
1NE	1-East	5740	146.0	3.50	E1	1-East	16.41	6.32	4.08	3.65
1SW	1-West	4910	146.4	3.00	W1	1-West	15.91	8.39	3.94	2.57
2NE	2-East	4780	143.6	2.00	E2	2-East	9.85	4.06	2.01	2.11
2SW	2-West	6270	142.8	-	W2	2-West	11.01	4.17	2.89	3.10
3NE	3-East	5620	147.5	2.80	E3	3-East	11.62	3.39	4.27	2.53
3SW	3-West	6730	145.2	3.30	W3	3-West	7.84	2.97	2.42	2.83
Average		5675	145.3	2.92	Average		12.11	4.88	3.27	2.80

Table 5.8 Core Compressive Strength, Unit Weight
Concrete Cover, and Chloride Content
Bridge # 7-40-6527, Jennings County

Core Number	Span	Minimum Compressive Strength (psi)	Unit Weight (lb/cu.ft)	Concrete Cover (in)	Sample Number	Span	Chloride Content (lb/cu.yd)			
							Level			
							A	B	C	D
							0-1 in.	1-2 in.	2-3 in.	3-4 in.
C-0-1E-1	0-1 East	4760	147.3	2.90	PC-1-2E-1	1-2 East	*	*	*	*
C-1-2E-2	1-2 East	6540	150.3	3.20	PC-2-3E-2	2-3 East	12.89	12.47	6.47	3.03
C-2-3E-3	2-3 East	5150	149.6	2.70	PC-0-1W-1	0-1 West	21.51	7.38	4.55	2.06
C-0-1W-1	0-1 West	5040	145.4	3.80	PC-0-1W-2	0-1 West	22.07	6.93	3.46	1.80
C-0-1W-2	0-1 West	4770	147.4	2.70	PC-0-1W-3	0-1 West	15.31	8.81	4.62	3.39
C-0-1W-3	0-1 West	5050	147.6	3.10	PC-1-2W-4	1-2 West	12.21	5.18	2.76	1.72
C-1-2W-4	1-2 West	4780	150.0	2.90	PC-1-2W-6	1-2 West	6.32	*	*	4.31
C-1-2W-5	1-2 West	7180	151.3	2.60	PC-2-3W-7	2-3 West	14.37	*	7.92	4.22
C-2-3W-6	2-3 West	5820	150.3	2.90	PC-2-3W-9	2-3 West	16.05	10.19	5.13	1.43
C-2-3W-7	2-3 West	5860	148.7	3.40						
Average		5495	148.8	3.02	Average		15.09	8.49	4.99	2.75

* Not enough material

Table 5.9 Summary of Field Evaluation

Bridge	Average Values of								Maximum Crack Width (in)
	Core Strength (psi)	Calculated Cylinder Strength	Unit Weight (lb/cu.ft)	Concrete Cover (in)	Chloride Content (lb/cu.yd)				
					Level				
					A	B	C	D	
	(psi)	(psi)	(lb/cu.ft)		0-1 in.	1-2 in.	2-3 in.	3-4 in.	
Downtown, Indianapolis (1985)	6038	5132	146.1	2.40	5.93	2.17	1.48	1.18	0.030
Downtown, South Bend (1983)	7483	6360	151.2	3.21	14.18	7.11	3.73	3.97	0.025
South of South Bend (1980)	6524	5545	148.9	2.44	17.76	12.15	3.21	1.61	0.030
Bartholomew County (1985)	6636	5640	154.9	3.82	7.14	2.79	1.09	0.80	0.035
Gary, Indiana (1980)	5675	4824	145.3	2.92	12.11	4.88	3.27	2.80	0.060
Jennings County (1976)	5495	4670	148.79	3.02	15.09	8.49	4.99	2.75	0.050

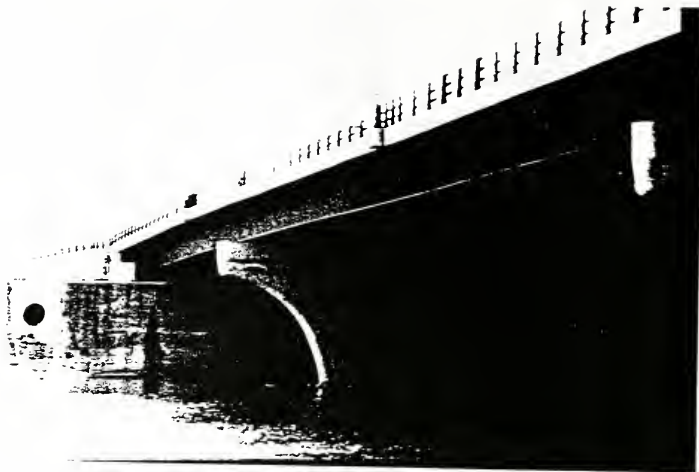


Figure 5.2 Bridge # 40-49-7032
(US 40, Marion County)

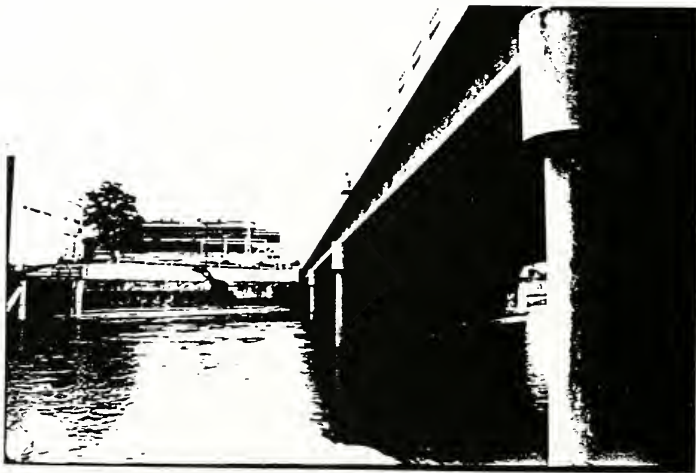


Figure 5.3 Bridge # 20-71-6538
(US-2, St. Joseph County)



Figure 5.4 Bridge # 31-50-2540
(US 31, Marshall County)



Figure 5.5 Bridge # 7-03-6797
(S.R.7, Bartholomew County)



Figure 5.6 Bridge # 912-45-6599
(S.R.912, Lake County)

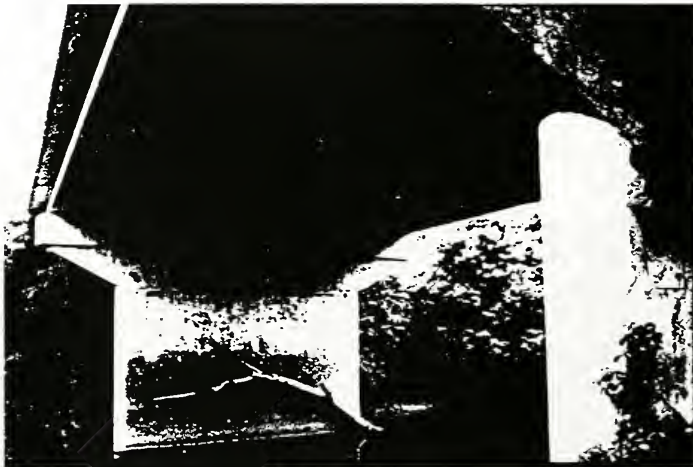


Figure 5.7 Bridge # 7-40-6527
(S.R.7, Jennings County)

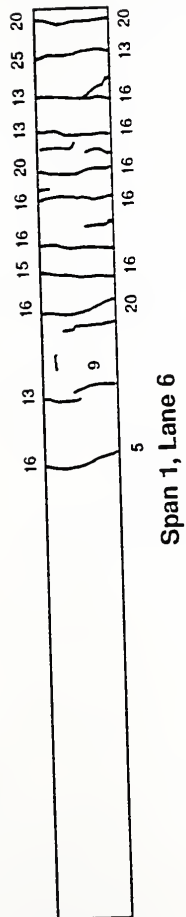
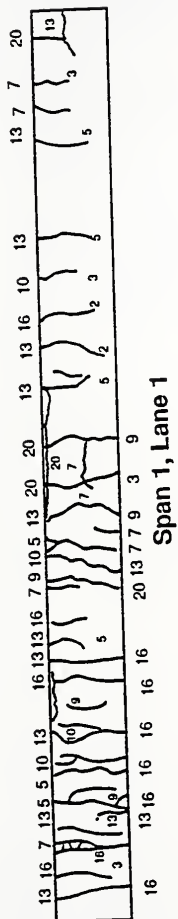


Figure 5.8 Crack Patterns, Bridge 40-49-7032
Span 1, Lane 1 and Lane 6

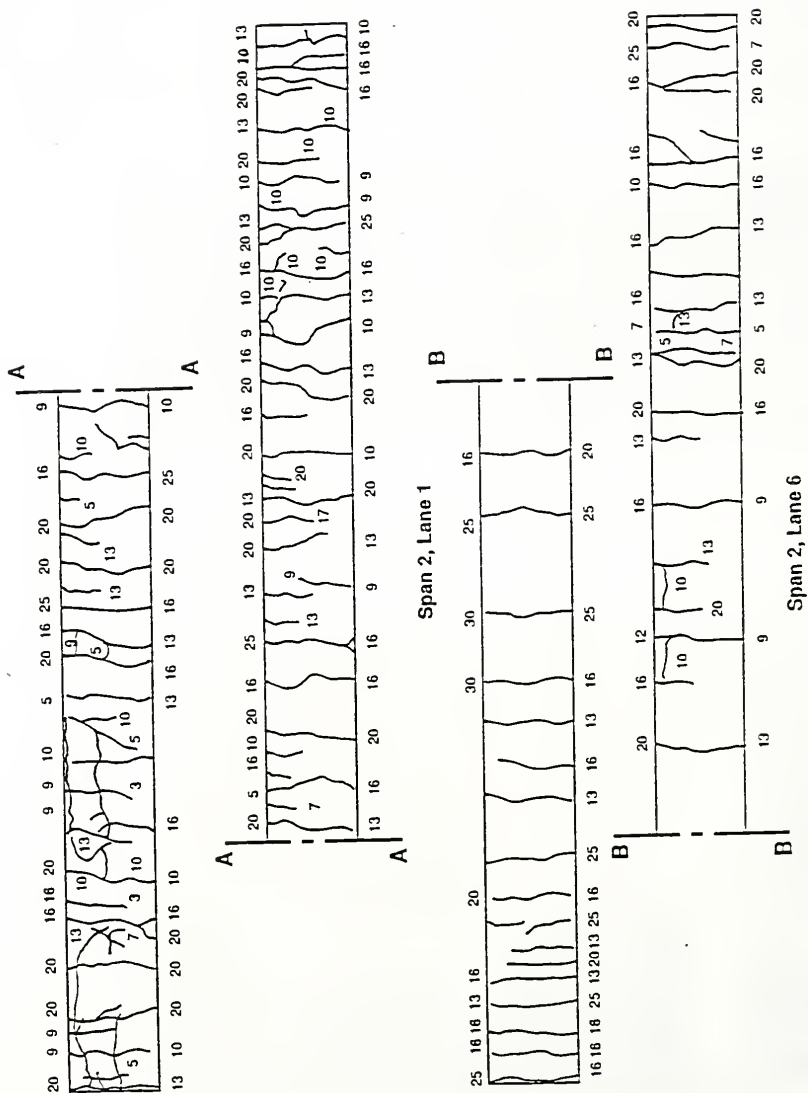
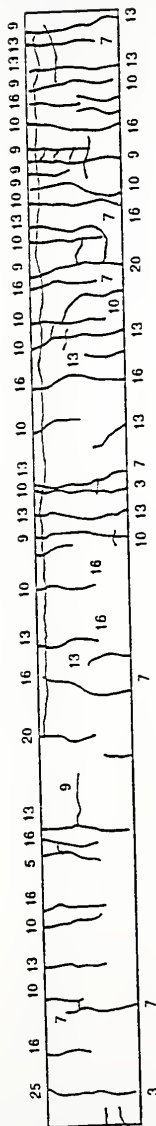
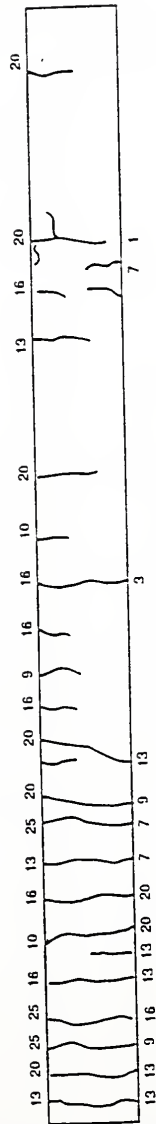


Figure 5.9 Crack Patterns, Bridge 40-49-7032
Span 2, Lane 1 and Lane 6

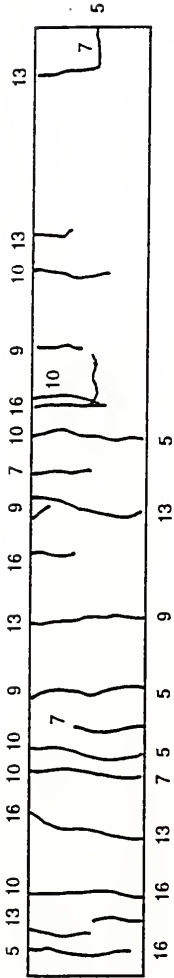


Span 3, Lane 1

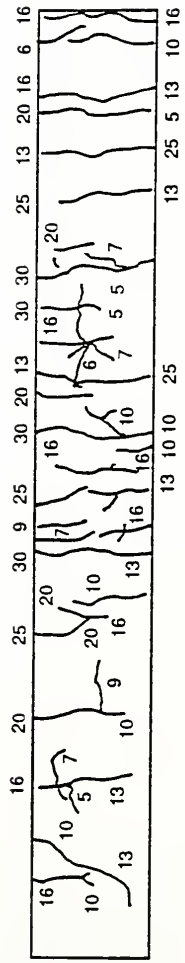


Span 3, Lane 6

Figure 5.10 Crack Patterns, Bridge 40-4970-32
Span 3, Lane 1 and Lane 6

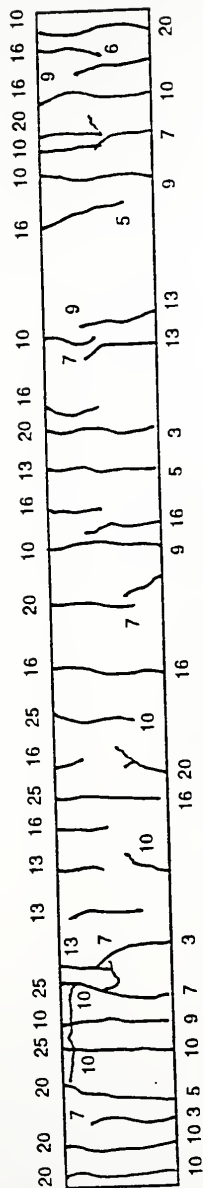


Span 4, Lane 1

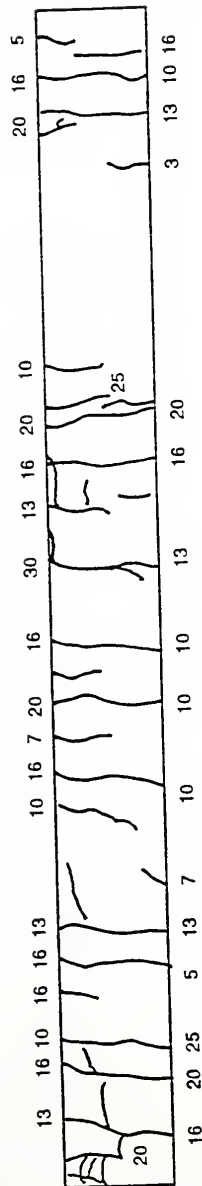


Span 4, Lane 6

Figure 5.11 Crack Patterns, Bridge 40-49-7032
Span 4, Lane 1 and Lane 6



Span 5, Lane 1



Span 5, Lane 6

Figure 5.12 Crack Patterns, Bridge 40-49-7032
Span 5, Lane 1 and Lane 6

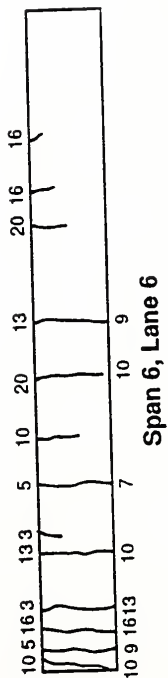
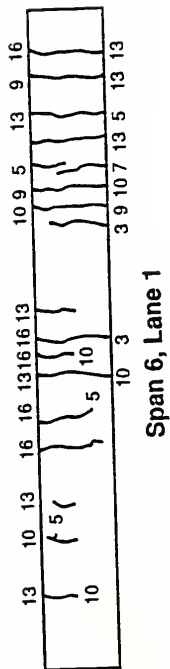


Figure 5.13 Crack Patterns, Bridge 40-49-7032
Span 6, Lane 1 and Lane 6

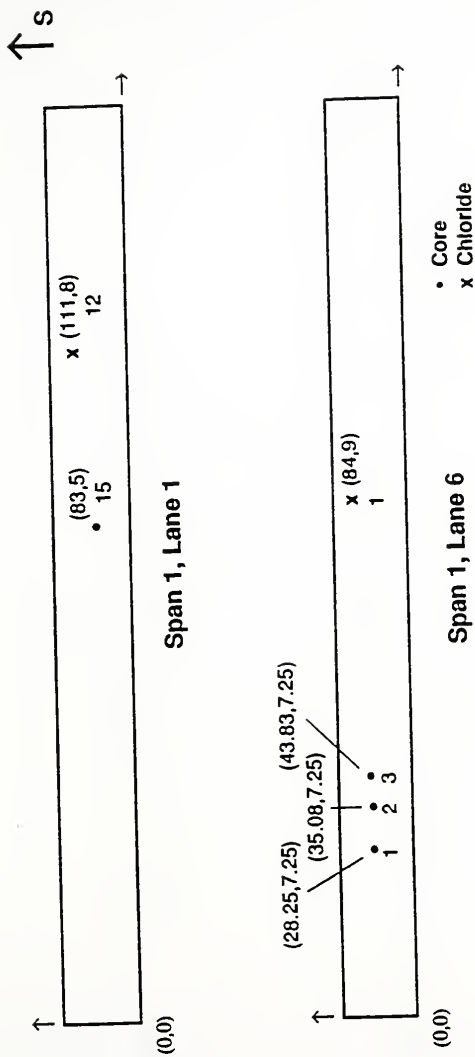


Figure 5.14 Core and Chloride Sampling, Bridge 40-49-7032
Span 1, Lane 1 and Lane 6

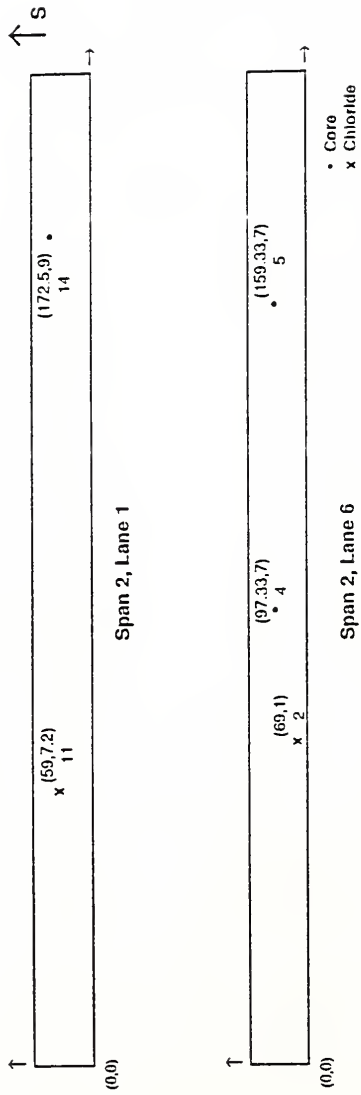


Figure 5.15 Core and Chloride Sampling, Bridge 40-49-7032
Span 2, Lane 1 and Lane 6

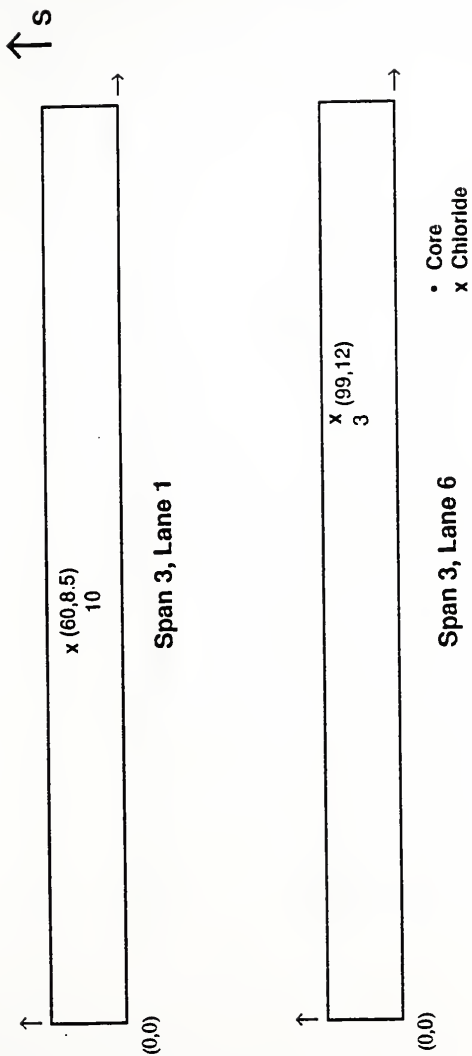


Figure 5.16 Core and Chloride Sampling, Bridge 40-49-7032
Span 3, Lane 1 and Lane 6

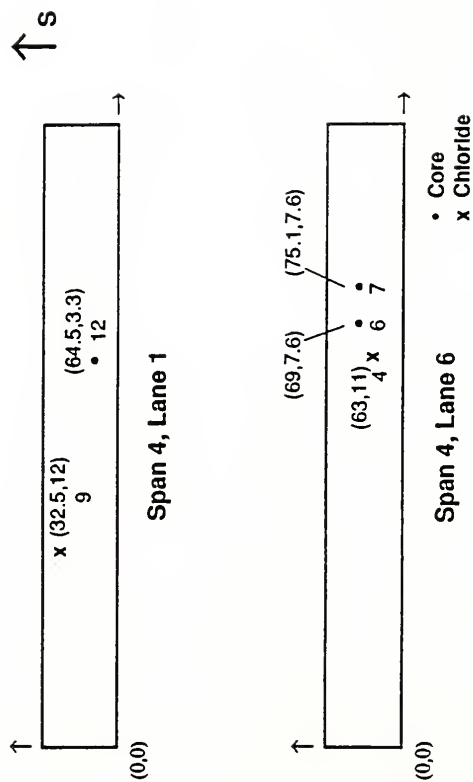


Figure 5.17 Core and Chloride Sampling, Bridge 40-49-7032
Span 4, Lane 1 and Lane 6

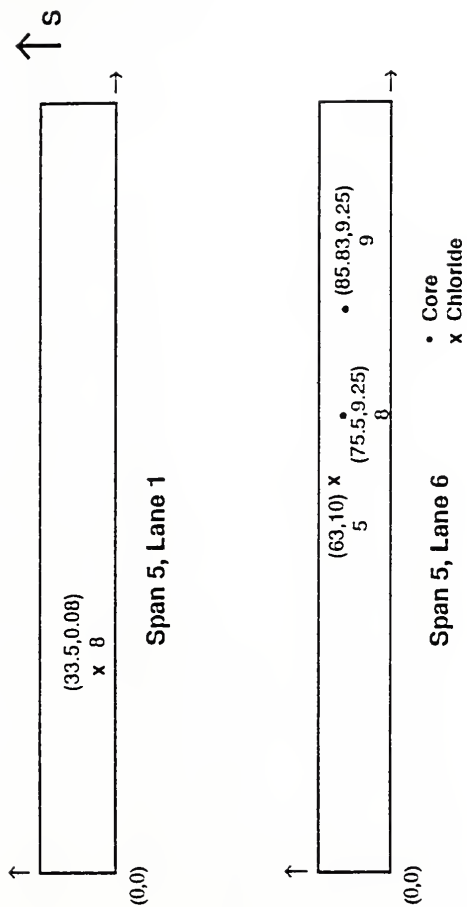


Figure 5.18 Core and Chloride Sampling, Bridge 40-49-7032
Span 5, Lane 1 and Lane 6

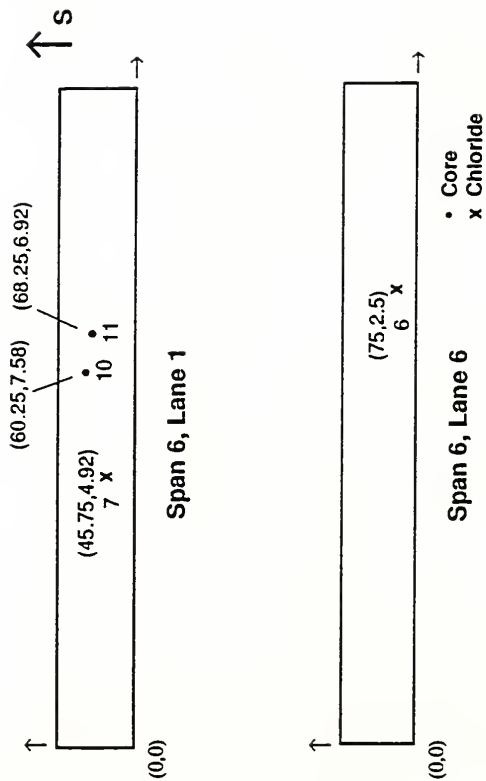
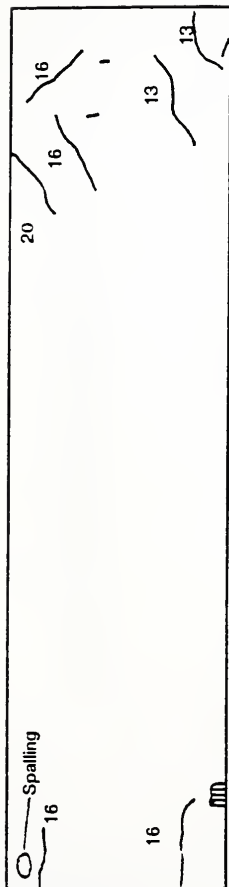
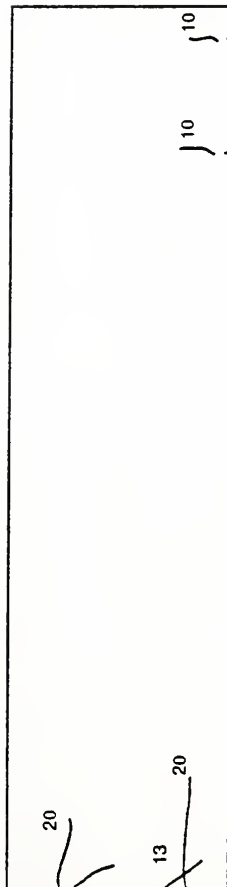


Figure 5.19 Core and Chloride Sampling, Bridge 40-49-7032
Span 6, Lane 1 and Lane 6

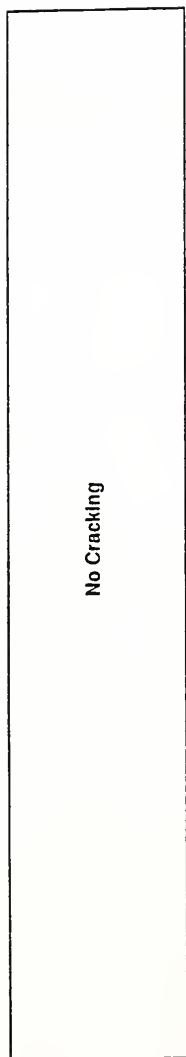


Span B-North



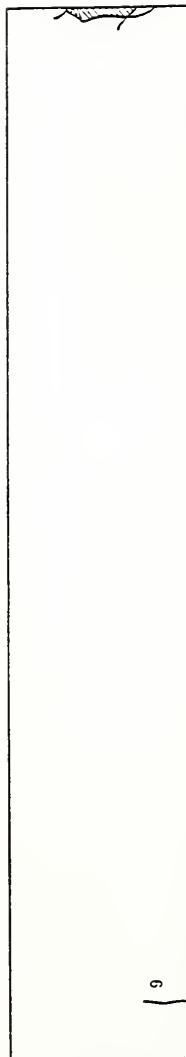
Span B-South

Figure 5.20 Crack Patterns, Bridge 20-71-6538
Span B-North and Span B-South



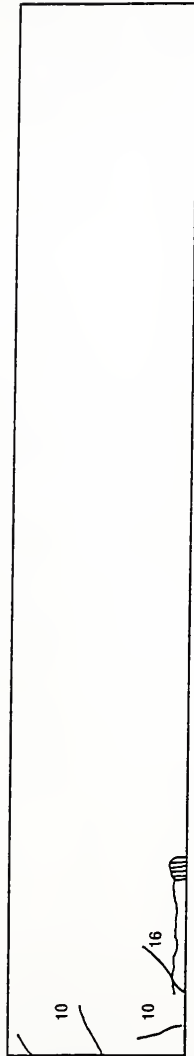
No Cracking

Span C-North



Span C-South

Figure 5.21 Crack Patterns, Bridge 20-71-6538
Span C-North and Span C-South

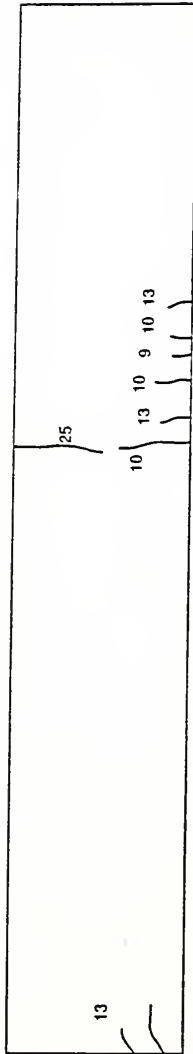


Span D-North

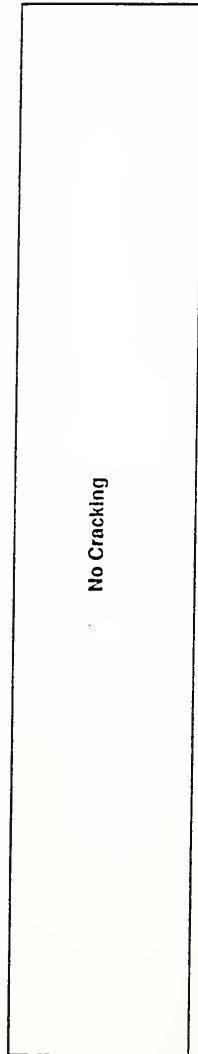


Span D-South

Figure 5.22 Crack Patterns, Bridge 20-71-6538
Span D-North and Span D-South



Span E-North



No Cracking

Span E-South

Figure 5.23 Crack Patterns, Bridge 20-71-6538
Span E-North and Span E-South

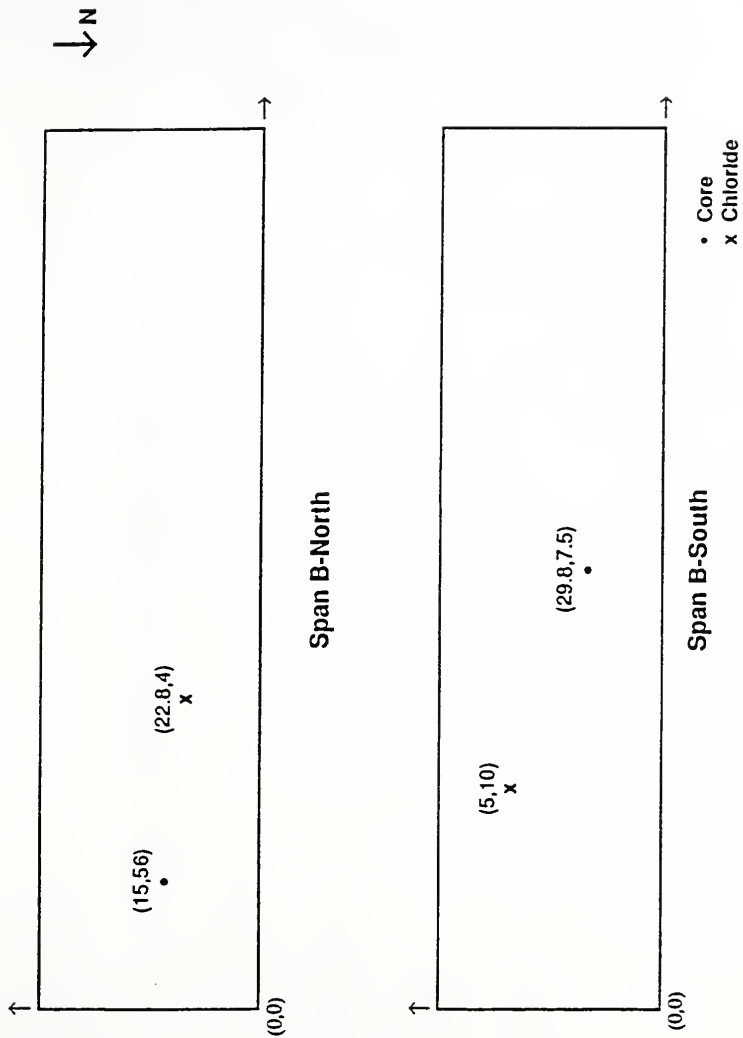


Figure 5.24 Core and Chloride Sampling, Bridge 20-71-6538
Span B-North and Span B-South

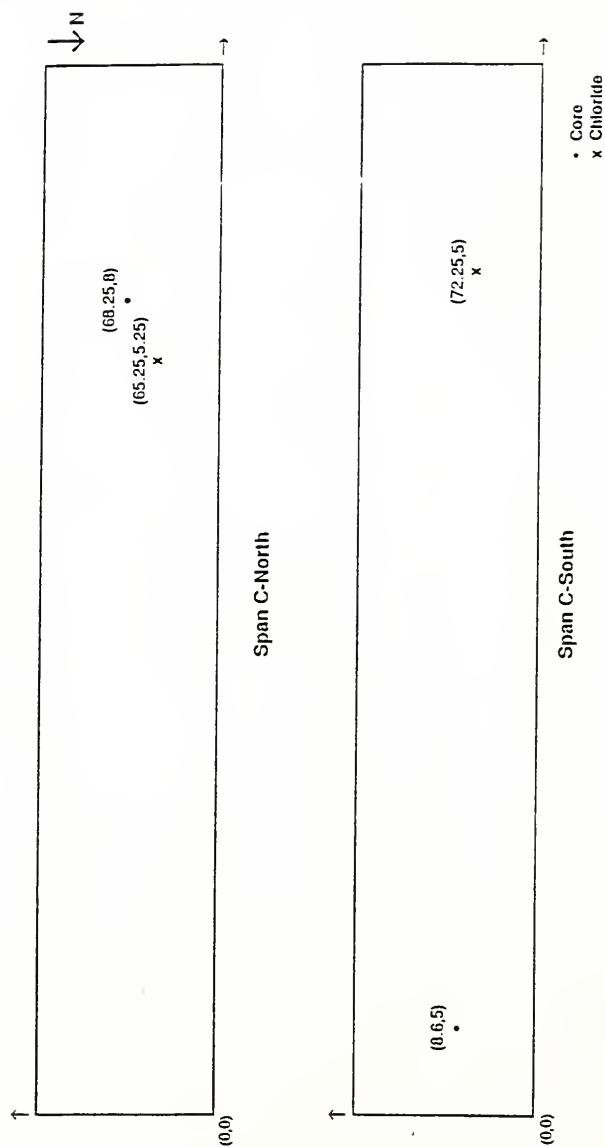


Figure 5.25 Core and Chloride Sampling, Bridge 20-71-6538
Span C-North and Span C-South

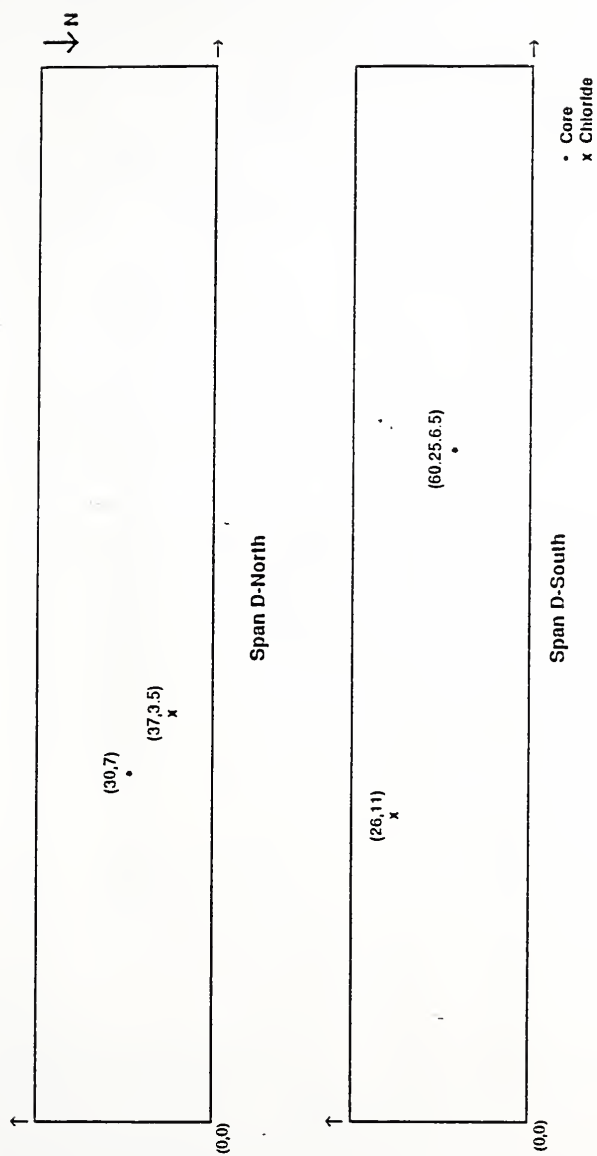


Figure 5.26 Core and Chloride Sampling, Bridge 20-71-6538
Span D-North and Span D-South

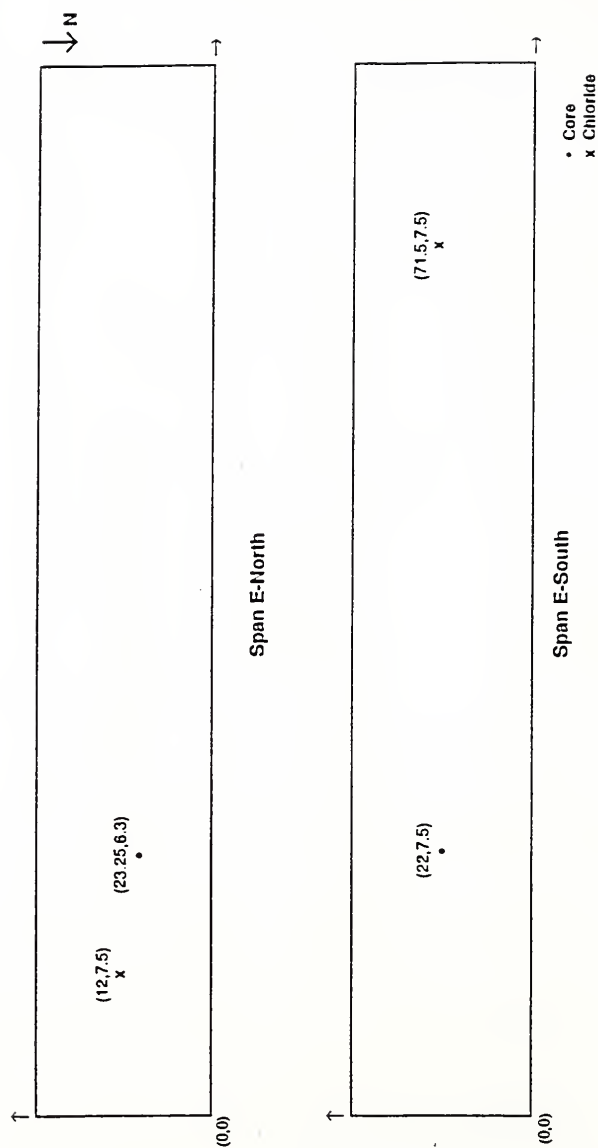
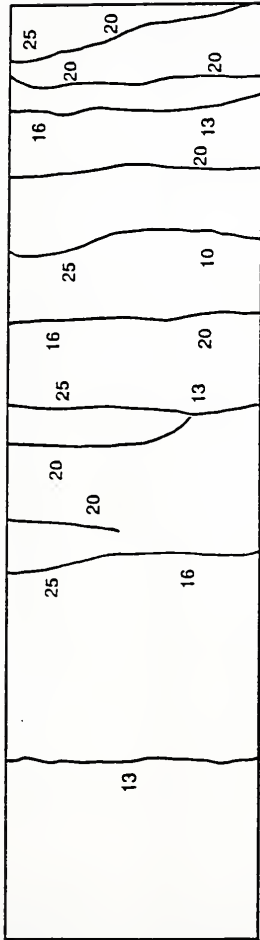
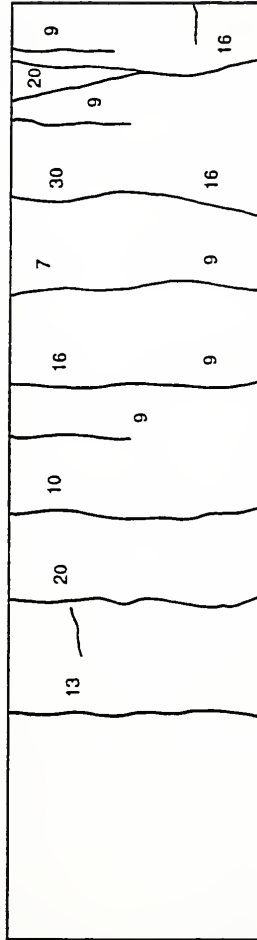


Figure 5.27 Core and Chloride Sampling, Bridge 20-71-6538
Span E-North and Span E-South



Span A-West



Span A-East

Figure 5.28 Crack Patterns, Bridge 31-50-2540
Span A-West and Span A-East

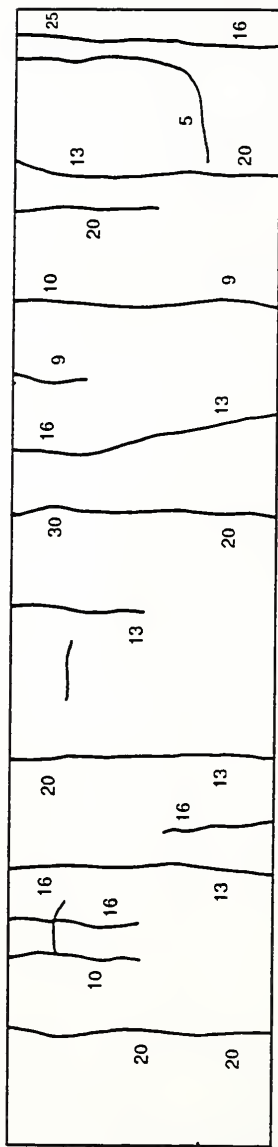
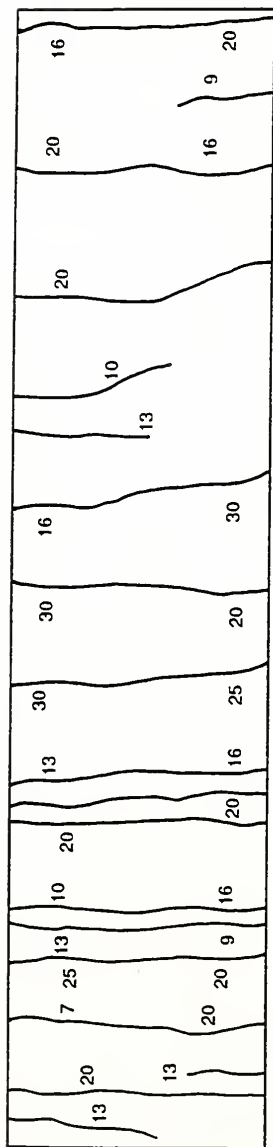
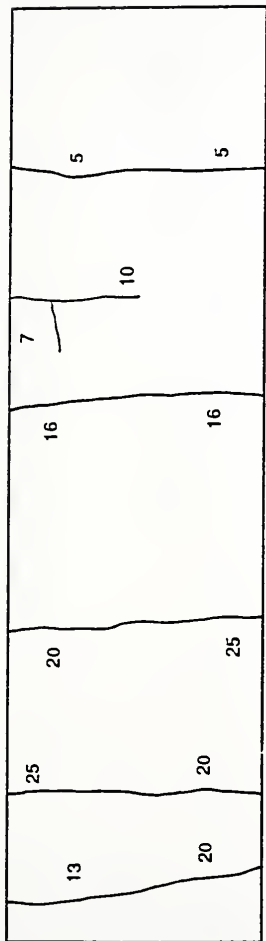
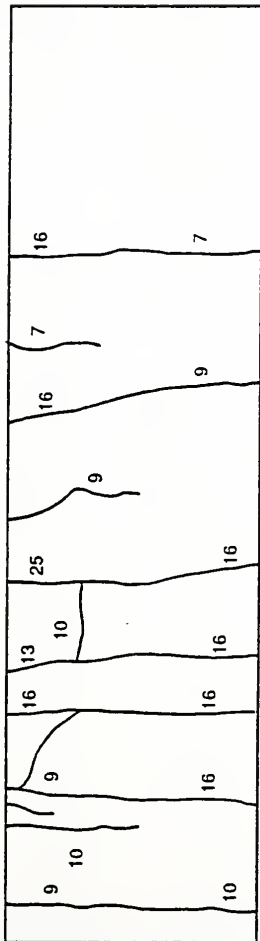


Figure 5.29 Crack Patterns, Bridge 31-50-2540
Span B-West and Span B-East



Span C-West



Span C-East

Figure 5.30 Crack Patterns, Bridge 31-50-2540
Span C-West and Span C-East

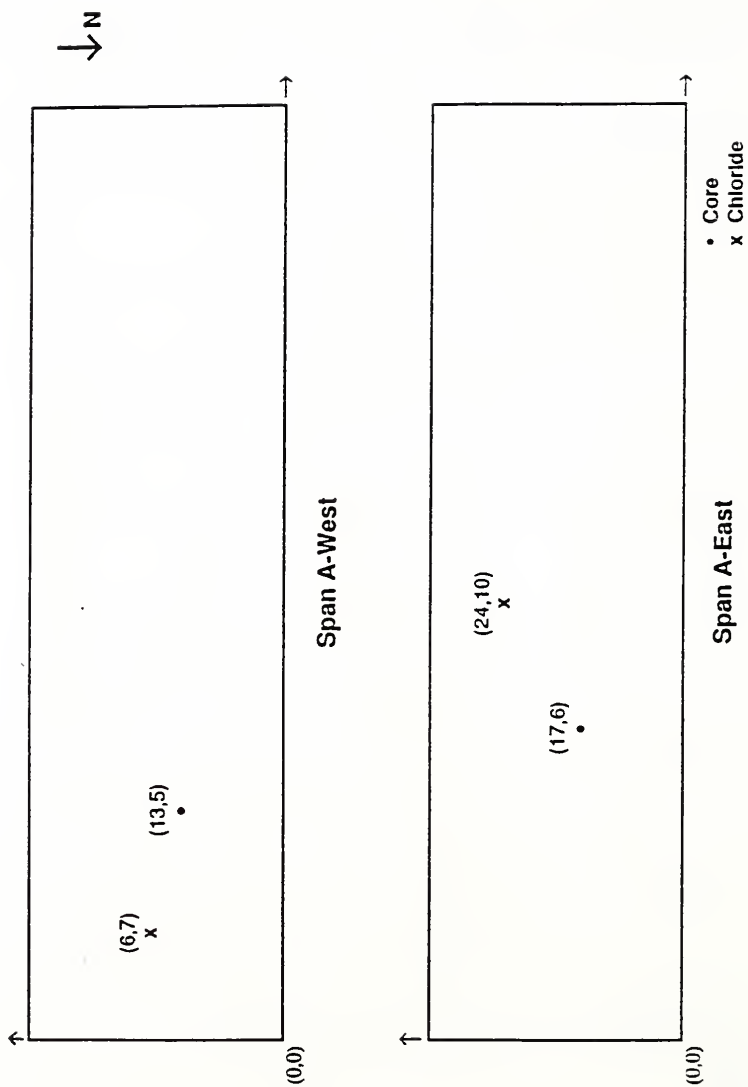


Figure 5.31 Core and Chloride Sampling, Bridge 31-50-2540
Span A-West and Span A-East

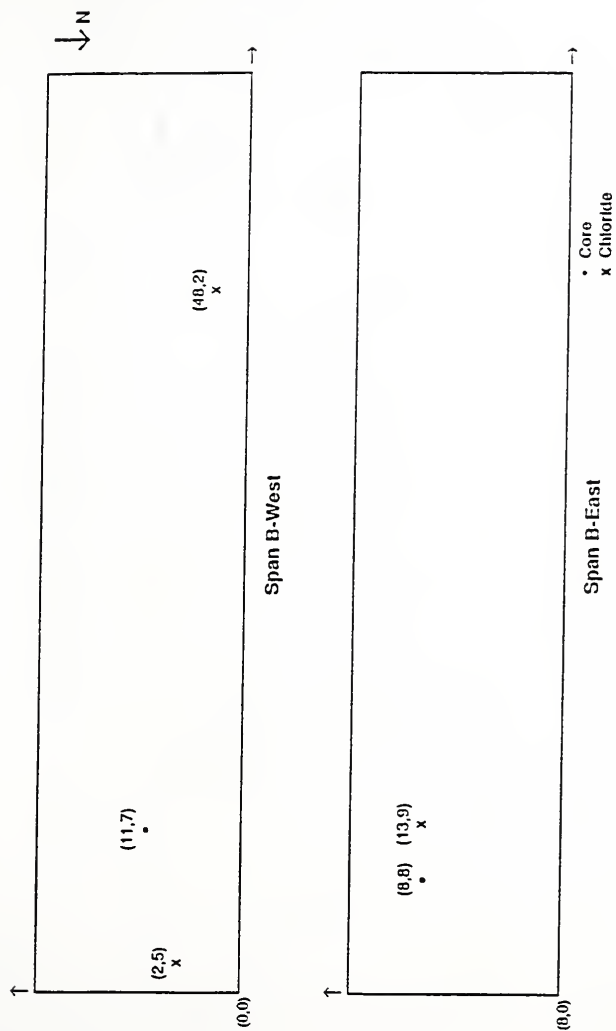


Figure 5.32 Core and Chloride Sampling, Bridge 31-50-2540
Span B-West and Span B-East

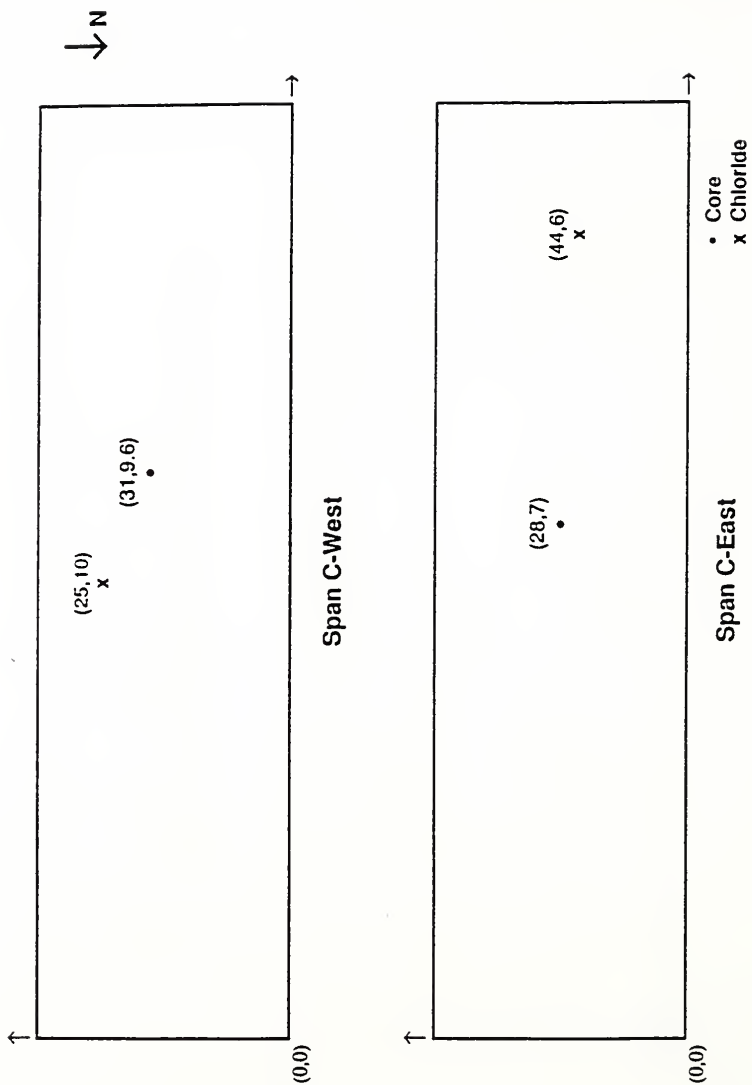


Figure 5.33 Core and Chloride Sampling, Bridge 31-50-2540
Span C-West and Span C-East

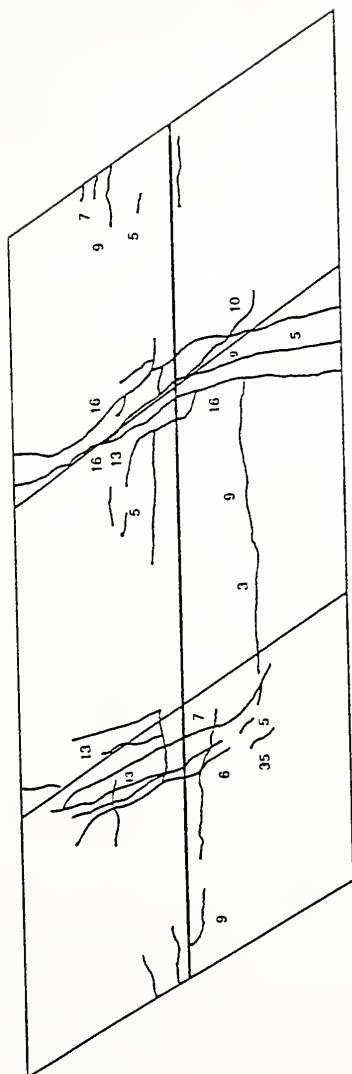


Figure 5.34 Crack Patterns, Bridge 7-03-6797

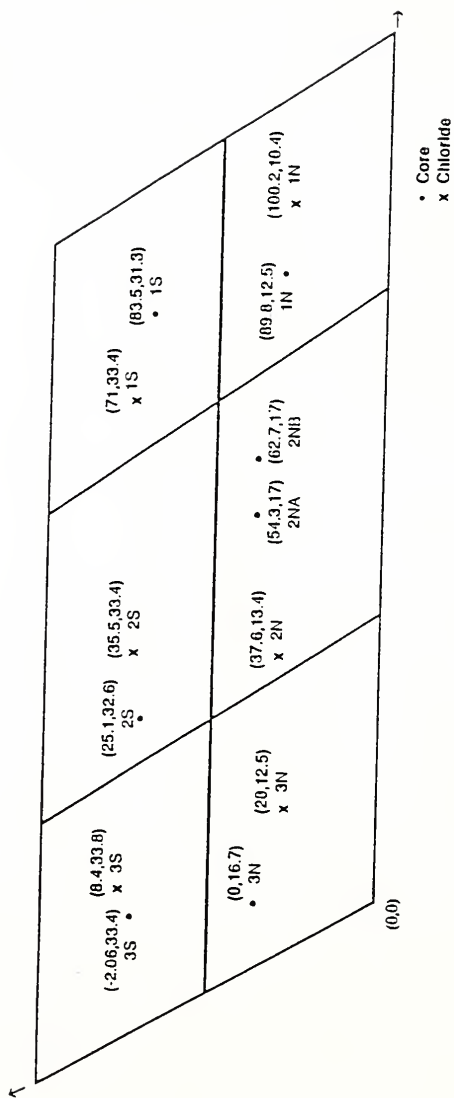
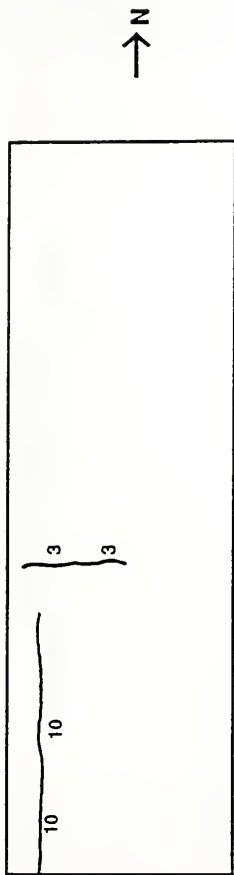
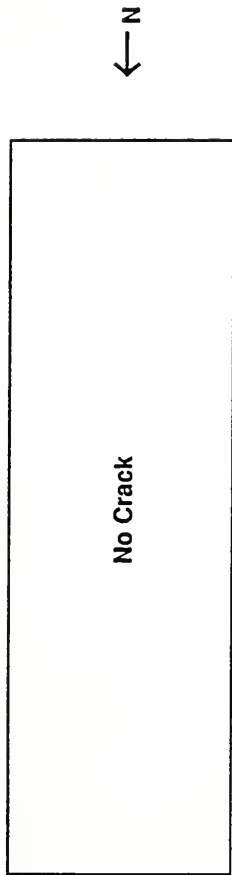


Figure 5.35 Core and Chloride Sampling, Bridge 7-03-6797

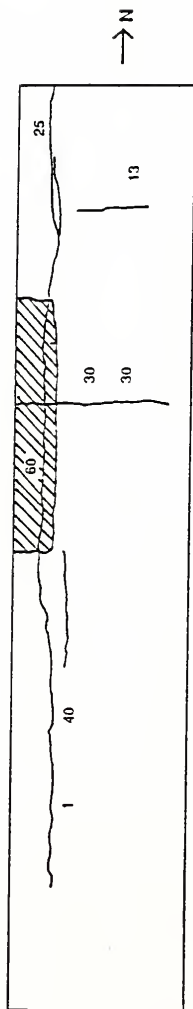


Span 1 NE

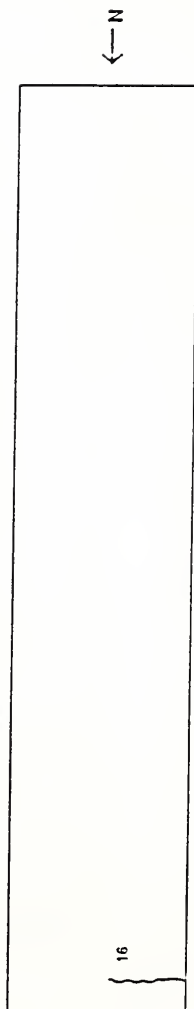


Span 1 SW

5.36 Crack Patterns, Bridge No. 912-45-6599
Span 1 NE and Span 1 SW

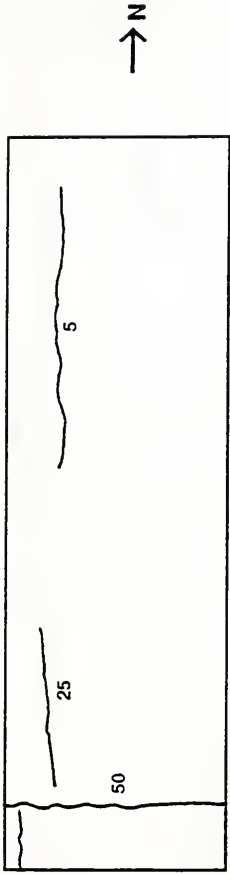


Span 2 NE

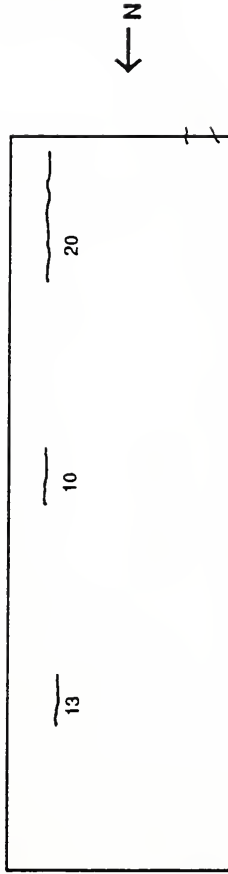


Span 2 SW

5.37 Crack Patterns, Bridge No. 912-45-6599 Span 2 NE and Span 2 SW

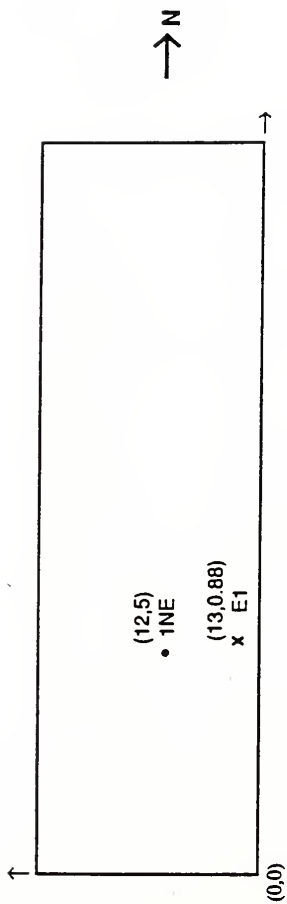


Span 3 NE

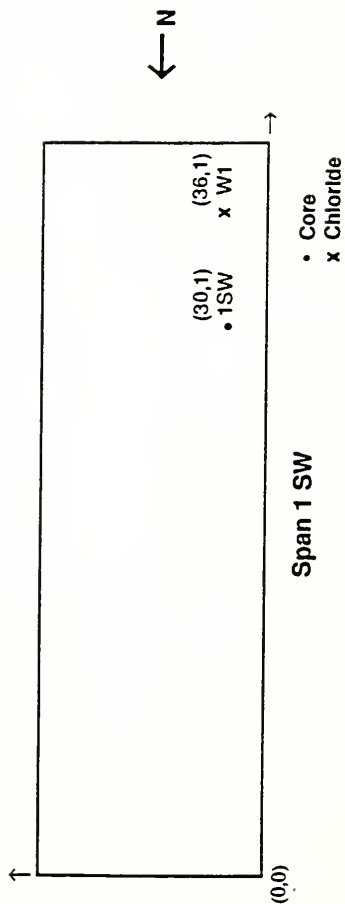


Span 3 SW

5.38 Crack Patterns, Bridge No. 912-45-6599
Span 3 NE and Span 3 SW

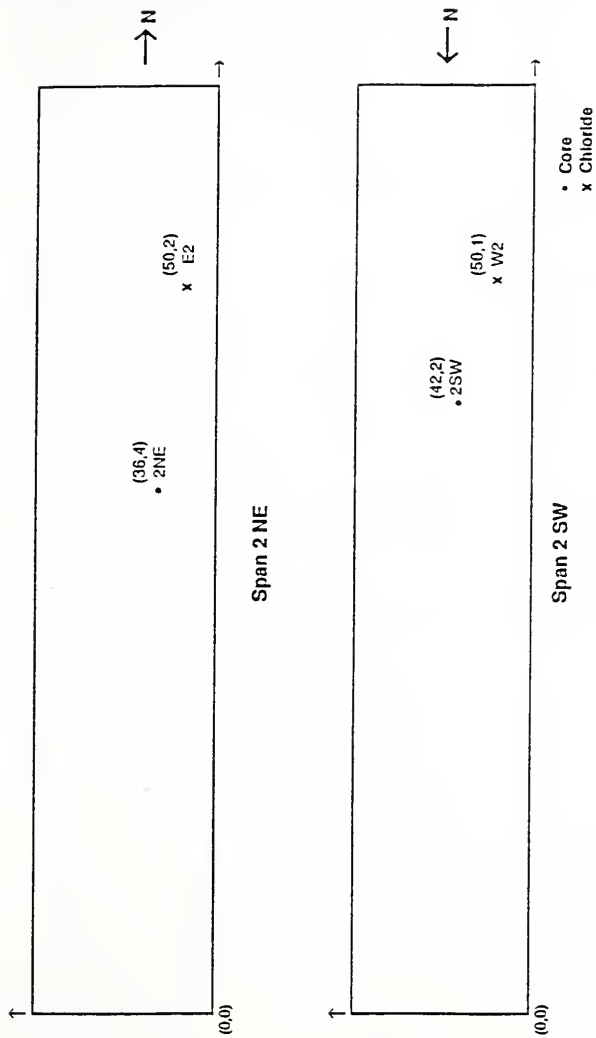


Span 1 NE

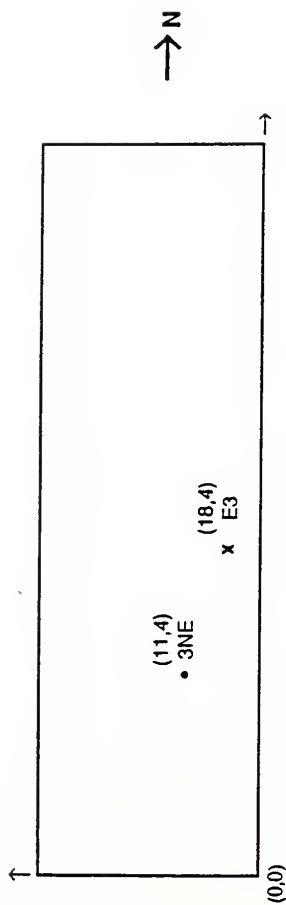


Span 1 SW

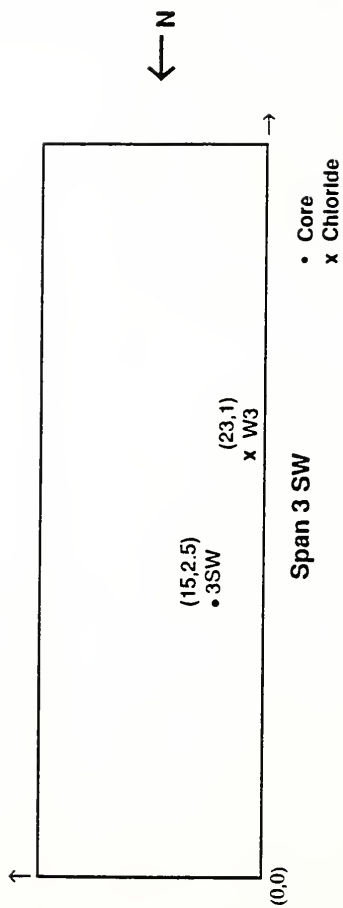
5.39 Core and Chloride Sampling, Bridge No. 912-45-6599
Span 1 NE and Span 1 SW



5.40 Core and Chloride Sampling, Bridge No. 912-45-6599
Span 2 NE and Span 2 SW

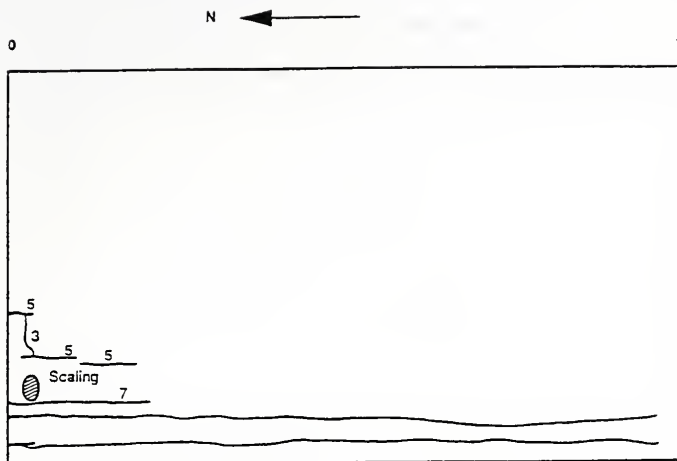


Span 3 NE



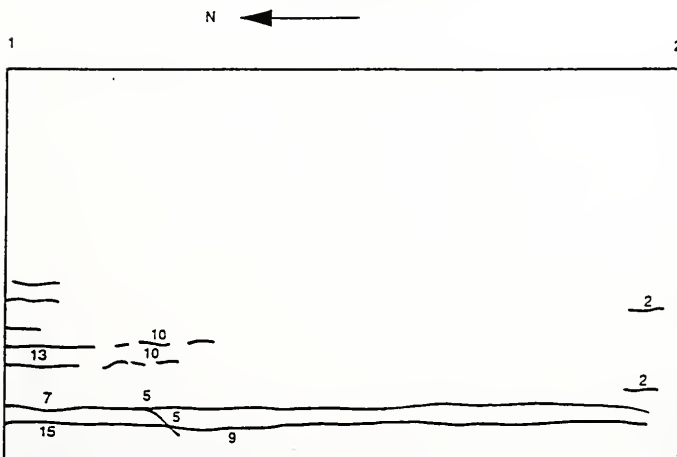
Span 3 SW

5.41 Core and Chloride Sampling, Bridge No. 912-45-6599
Span 3 NE and Span 3 SW



Span 0-1, East

Figure 5.42 Crack Patterns, Bridge # 7-40-6527
Span 0-1 East



Span 1-2, East

Figure 5.43 Crack Patterns, Bridge # 7-40-6527
Span 1-2 East

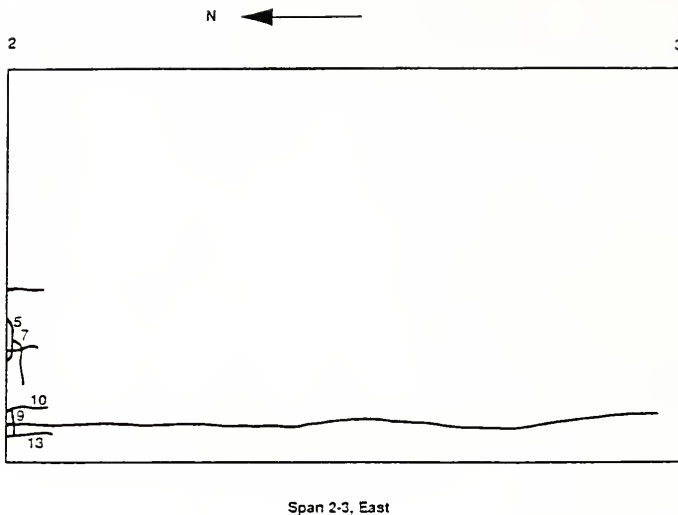


Figure 5.44 Crack Patterns, Bridge # 7-40-6527
Span 2-3 East

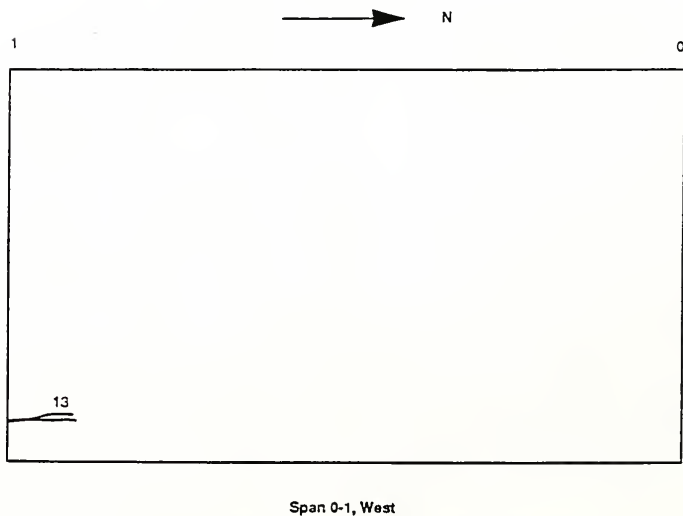


Figure 5.45 Crack Patterns, Bridge # 7-40-6527
Span 0-1 West

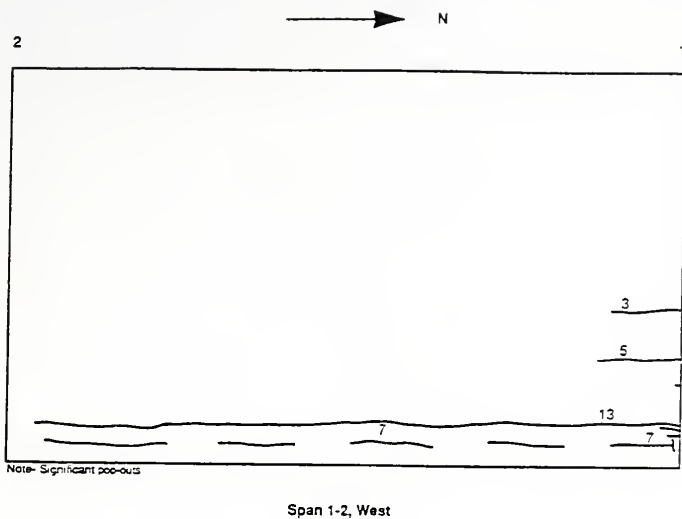


Figure 5.46 Crack Patterns, Bridge # 7-40-6527
Span 1-2 West

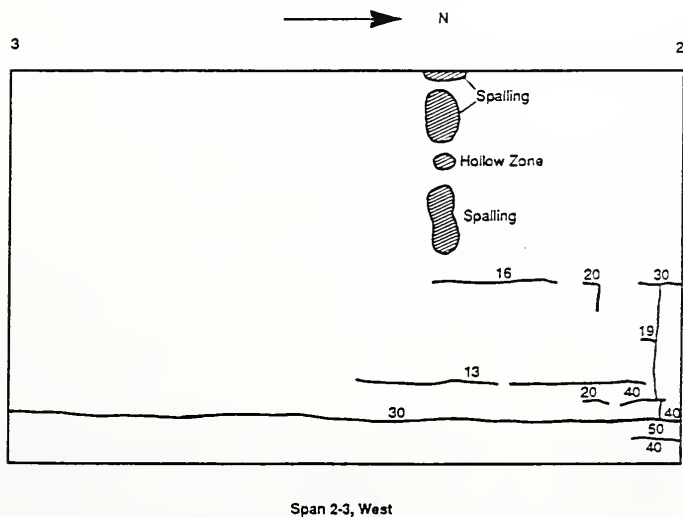


Figure 5.47 Crack Patterns, Bridge # 7-40-6527
Span 2-3 West

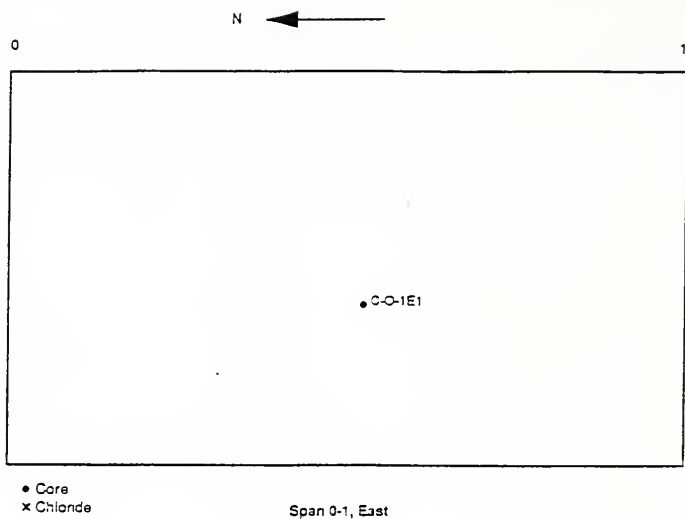


Figure 5.48 Core and Chloride Sampling, Bridge # 7-40-6527
Span 0-1 East

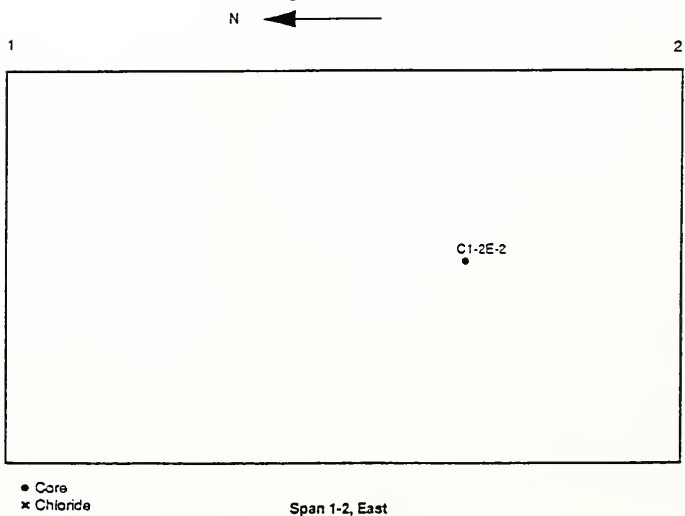


Figure 5.49 Core and Chloride Sampling, Bridge # 7-40-6527
Span 1-2 East

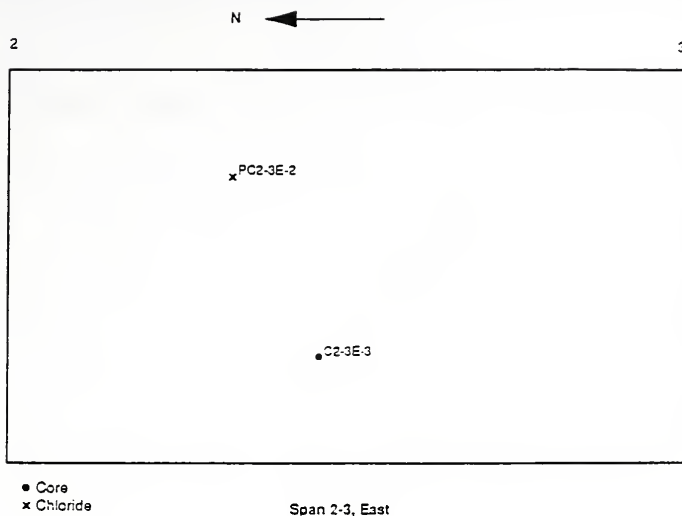


Figure 5.50 Core and Chloride Sampling, Bridge # 7-40-6527
Span 2-3 East

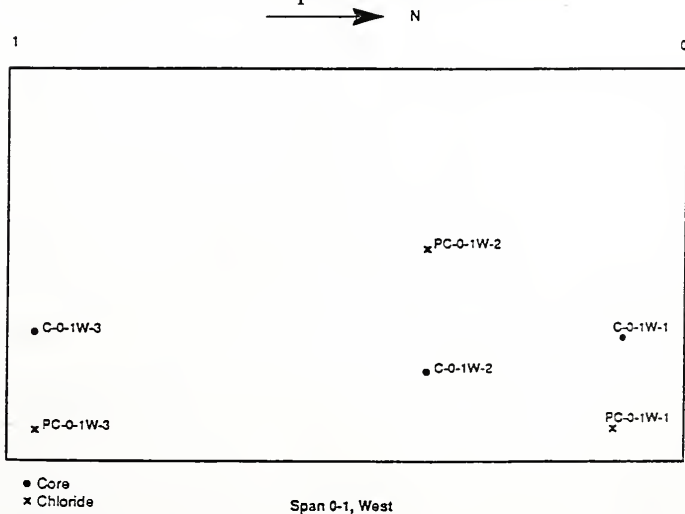


Figure 5.51 Core and Chloride Sampling, Bridge # 7-40-6527
Span 0-1 West

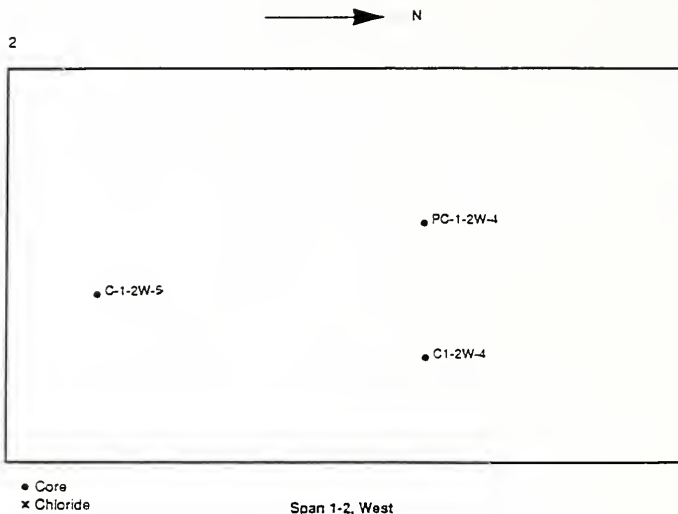


Figure 5.52 Core and Chloride Sampling, Bridge # 7-40-6527
Span 1-2 West

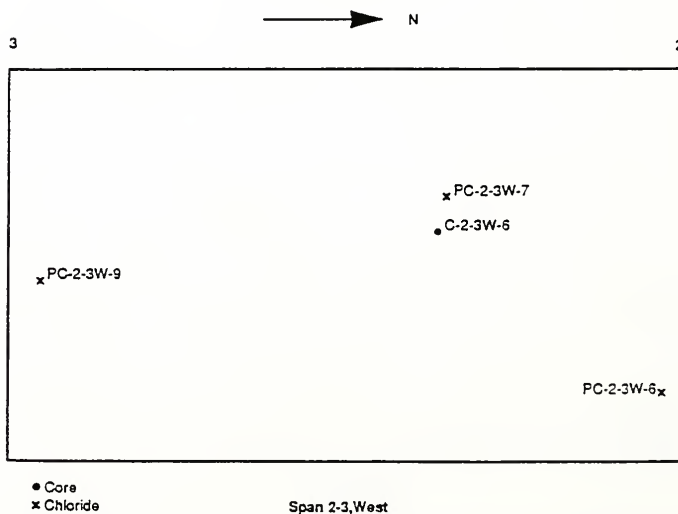


Figure 5.53 Core and Chloride Sampling, Bridge # 7-40-6527
Span 2-3 West

CHAPTER 6 SUMMARY, CONCLUSIONS, And RECOMMENDATIONS

6.1 Summary

In this study a Laboratory Phase and a Field Phase were conducted. The laboratory investigations were conducted to evaluate the structural performance of concrete slabs reinforced with epoxy-coated steel subjected to high cycle repeated loading. The evaluation was conducted by comparing the behavior of specimens reinforced with epoxy-coated steel to that of companion specimens reinforced with uncoated steel under service load conditions and at failure. The comparative study included deflections, cracking, fatigue, and bond. Thirty four reinforced concrete slab specimens of two types were tested to examine the influence of factors including concrete compressive strength, bar deformation pattern, coating thickness, splice length, peak stress, stress range, and mean stress. Of the thirty four slab specimens tested, thirty slabs were tested under repeated loading, and four were tested with a single loading cycle. The field study aimed at the condition assessment of concrete bridge decks reinforced with epoxy-coated steel in Indiana includes concrete cover measurements, extent and width of cracks, chloride content, concrete compressive strength, and epoxy rebar condition. Six bridges, representing a wide range of structures in service life, traffic condition, and intensity of salt application were selected for the evaluation. The conclusions and recommendations based on the observation and analysis of the results are presented in the following sections.

6.2. Conclusions of the Laboratory Phase

6.2.1 Deflection

1. For Type A specimens, the total deflection of specimens with epoxy-coated bars exceeded those of specimens with uncoated reinforcement by 5.4 % at the 2nd load cycle and reduced to 3.5 % after 1 million cycles. Repeated loading increased the deflections for both specimens with uncoated steel or coated bars. However, the changes were larger in specimens with uncoated reinforcement. The largest changes in deflection occurred in the first 200,000 cycles.
2. Specimens with uncoated steel had larger ductility in the splitting mode of failure. Observations of splitting behavior demonstrated that, compared to specimens with epoxy-coated steel, specimens with uncoated steel were able to carry approximately twice as much additional load after splitting and sustain larger deformations. This indicates a more brittle failure mode of the specimens with epoxy-coated reinforcement.
3. The effect of extra coating thickness is more significant for the members reinforced with smaller diameter bars. Specimens with extra thickness of coating had larger total deflection. However, for members with large diameter bars (Type B specimen), no significant differences in deflection were found between members with normal coating thickness and members with extra thickness of coating. Comparison of the very limited data indicates that members containing bars with diamond deformation pattern (series 1130DX) had larger cyclic deflection

compared to specimens with a spiral deformation pattern (series 1130SX). The splitting and failure loads as well as splitting and failure deflections were lower for the specimens with bars having a diamond deformation pattern compared to those reinforced with a spiral deformation pattern bars.

4. The peak stress significantly affects the maximum deflection at peak repeated load (representing service load level). Specimens with higher peak stress produce larger maximum deflection. Peak stress also influences the splitting and failure deflections for uncoated specimens. For specimens with uncoated steel, lower peak stress resulted in smaller splitting as well as failure deflections. No conclusive comment on the effect of peak stress on splitting and failure deflection can be made for specimens with epoxy-coated reinforcement.
5. Higher stress range resulted in larger splitting deflections and a larger increment in deflection between the cyclic phase for specimens with uncoated bars and also for specimens with epoxy-coated bars. Higher stress range also gives higher failure deflection for uncoated specimens. However, for specimens with epoxy-coated bars, the influence of stress range on failure deflection is not clear. No clear indication of the effect of peak stress and stress range on E/U ratios of deflection has been found.

6.2.2 Cracking

1. Fewer but wider flexural cracks were found for members with epoxy-coated steel. The total crack width of epoxy-coated specimens is greater than that of uncoated

specimens. However, the difference is reduced by the repeated loading.

2. The flexural cracking load of members with epoxy-coated reinforcement was, although not significantly, lower than that of members with uncoated bars. The splitting cracking load was also lower for epoxy-coated specimens. The average E/U ratios of cracking loads for Type A specimens was 0.924, and 0.941 for Type B specimens.
3. The combination of c/d_b and l/d_b ratio is a dominant factor that influences the splitting load. Hypothetically there would be an optimum combination of these ratios that gives the optimum splitting load.
4. For uncoated specimens, test results consistently showed that an increase in mean stress led to an increase in the failure load. Also, approximately 80% of the repeated load tests showed that higher mean stress produced a higher splitting load for uncoated specimens. Nevertheless, the influences of mean stress on splitting load disagree with those presented in a previous study by Cleary and Ramirez [11]. Future works are needed to clarify this matter.
5. Stress range influences the splitting load. Observation on the effect of stress range showed that all but one of the three ranges considered showed that higher stress range resulted in lower splitting load. This agrees with previous work by Cleary and Ramirez [11].
6. No conclusion can be drawn on the effect of coating thickness on crack widths. Results of tests on diamond deformation pattern provide an indication that members with a diamond deformation pattern might have larger crack widths

compared to members with spiral deformation pattern. More data are needed.

6.2.3 Bond Strength

1. A higher concrete compressive strength resulted in a lower bond ratio.
2. The effect of stress range on bond ratio is still unclear.
3. The influence of extra-thickness of coating on bond ratio is not significant. The result of diamond deformation pattern indicates that the bond ratio decreases as relative rib area or bearing area ratio decreases.
4. The Orangun equation [14] gives good results in predicting the bond stress for uncoated bars. However, it results in a conservative estimate of the failure stress for epoxy-coated bars.
5. The ACI 318-89 provisions on splices with epoxy-coated bars are over-conservative.
6. The use of a single modification factor for epoxy-coated bars as suggested by Hester et. al is justified by the results of this and the Cleary and Ramirez [11] studies.
7. Hester et al. suggestion of a 1.35 epoxy coating modification factor is in agreement with the factor for epoxy-coated bars of 1.33 found in this study.

6.3 Findings from Field Investigation

1. Chloride concentration is significantly decreased with the increase in concrete cover.

2. Except for the Bartholomew County bridge, all the other five bridge decks were under exposure to chlorides well above the corrosion threshold value at the level of the reinforcing steel.
3. No sign of debonding of the coating or corrosion was observed in the reinforcing bar samples extracted from the bridges decks studied.
4. The combination of adequate cover and the use of epoxy-coated steel has provided a good corrosion protection in the bridge decks surveyed.

In summary, besides providing a better protection against the corrosion, extra concrete cover also provides better conditions for anchorage of the bars. Larger cover to diameter ratios are also recommended in harsh environments to reduce the crack opening and should not be reduced with the expectation that the epoxy-coating will be the sole system of corrosion protection system. Adequate inspection, finishing and curing represent solid construction practice and will lead to durable concrete. The use, proper manufacturing and handling of epoxy-coated bars are but a few of the aspects related to durable concrete bridge decks.

6.4 Recommendations

1. The application of a single modification factor for epoxy-coated bars as suggested by Hester et al. [6] of 1.35 is supported by the findings of this research study.
2. Larger cover to bar diameter ratios (1.8 and higher) are recommended in harsh environments to reduce the crack opening and should not be reduced with the expectation that the epoxy-coating will be the sole system of corrosion protection.

3. Additional research is needed to clarify the long term effectiveness and durability of epoxy-coated steel as a corrosion protection system for highway and bridge structures.

6.5 Area For Future Works

Some of the areas for future works are the following:

1. Although no corrosion and debonding was found from the epoxy-steel samples taken from the cores, continuous laboratory research and field monitoring on the durability of epoxy-coating are still needed as the controversy in this issue still exists.
2. There is little knowledge on the behavior of concrete members reinforced with epoxy-coated steel under seismic loading, the most common case of low-cycle loading. Thus, because of the potential for severe damage and disaster that can be caused by an earthquake, research in this area is justified.

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